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EXPERIMENT SUPPORT SOFTWARE TECHNIQUES ANALYSIS (FPE 5.3A)

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ABSTRACT

This document presents the results of a five month's study of the image data processing techniques that may be required on board a manned Space Station to support an X-ray Imaging Solar Telescope. The various techniques required are described and flow charts of their basic operation are presented. Each technique is evaluated with respect to its usefulness in support of the experiment and its requirements for computer run time. A section is devoted to the hardware implications of providing image processing facilities for the experiment in space and a final section offers observations and conclusions made by the project team during the period of performance. The work was performed under contract number NAS8-25471 for the Computation Laboratory of the George C. Marshall Space Flight Center, Huntsville, Alabama.

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FOREWORD

Early plans for the development of the Saturn series of large space boosters made allowance for a possible failure of a number of initial flight tests. These plans were based on testing programs such as Jupiter and Thor where several initial launching attempts failed to achieve satisfactory results. Unexpected early successes in Saturn development, however, placed NASA planners in the somewhat embarrassing position of not having payloads to go with their launches. The problem was quickly solved by the construction of the Pegasus series of meteorite detection satellites. Government planners are now threatened with a similar problem in that no longer must their primary concern be the challenge of putting men and experiments into space. The challenge now lies in developing experiments which take full advantage of our space launch capabilities, and in the efficient and thorough analysis and dissemination of the scientific data produced by such space experiments.

Although the volume of raw data produced by future space experiments may be considerable, in most instances, the expected rate of improvement in computer technology, both in speed and capacity, should provide hardware which is equal to the required information processing tasks. The real challenge to information processing in the coming generation of space experiments is in the field of software development. Writing in an article for the Air Force, B. W. Boehm states, "Most military space operations during the 1970's will not strain our available information-processing capabilities. But some operations--real-time image processing, STS (Space Transportation System) on-board computing, multisensor data analysis, and decision oriented displays particularly--will not permit the Air Force to reach "on the shelf" and find tools for the job."[1] This is true for NASA space operations as well.

As a result of work performed during Phase B of the NASA study contract NAS8-25471, "Analyses of the Requirements for Computer Control and Data Processing Experiment Subsystems," the System Development Corporation recommended that "work be initiated to develop new and more efficient methods for processing, compressing, enhancing, transmitting and analyzing image data." This report is the result of an extension to that contract. It is one of two documents produced under NASA study contract NAS8-25471 (Modification Number 4). A second report, SDC TM-(L)-HU-033/003/00, presents a software design for the in-space computer support of a Grazing Incidence X-ray Polarimeter experiment (FPE 5.1). Both documents were prepared for the Computer Systems Division of the George C. Marshall Space Flight Center's Computation Laboratory by the System Development Corporation's Huntsville Space Projects staff. The work was performed under the general technical direction of Mr. Bobby C. Hodges who was the Contracting Officer's Representative for the project. Appreciation is expressed to Mr. Hodges, Mr. Doug Thomas, and Dr. E. H. Hopper of the MSFC Computation Laboratory and to Dr. J. E. Milligan of the Space Sciences Laboratory for their valuable support and technical assistance during the course of this project.

SECTION 1. INTRODUCTION

The past decade has seen much work directed toward the use of programmable digital computers for image improvement and analysis. In applications such as chromosome classification, fingerprint analysis, aerial surveillance, and alphanumeric character recognition, a high level of sophistication already has been achieved. However, the use of similar techniques for the support of the scientists in space poses new and unique challenges to the computer systems developer.

In an earlier report,* System Development Corporation presented the results of a study to support the data processing requirements of a spaceborne X-ray imaging solar telescope (FPE 5.3A). In the report SDC developed a general configuration for a computer system to support the scientific investigations in space that are proposed for Space Station experiment FPE 5.3A. Special emphasis was placed on the computer software needed to retrieve, analyze, and present primary experiment data produced by the experiment in the form of photographic images. In addition, SDC recommended that "work be initiated to develop new and more efficient methods for processing, compressing, enhancing, transmitting and analyzing image data." As a result of this recommendation, SDC was asked to study those image processing operations needed to support the X-ray Imaging Solar Telescope experiment (FPE 5.3A). Such emphasis on software techniques for image data processing is justified when the proportion of primary data that will be produced in image form is compared to that in non-image form. More than 75% of the primary data bits generated by presently proposed space experiments is produced as electronic or photographic imagry.

1.1 Project Objectives

The purpose of this project has been to compile computer techniques for specific experiment data analysis requirements, and to test and evaluate the techniques

*TM-(L)-HU-033/002/00, "Expanded Specifications for Experiment Control and Data Processing Requirements - Phase B," 20 October 1970.

considered, to demonstrate their unique capabilities and limitations. There has been no intent to design operational computer software for Space Station experiments, but rather the intent has been to establish a baseline of usable approaches with which to make estimates of the system design restraints and capacities. It is believed that by developing such usable computer techniques for a few representative experiments, realistic judgements of the facilities required, development effort called for, and capabilities provided, can be estimated for the Space Station experiment data processing system as a whole. Specifically, this report sets forth the preliminary technique design for eighteen image processing operations needed to support the X-ray Imaging Solar Telescope Experiment (FPE 5.3A) and draws conclusions as to the capabilities, limitations, and operational efficiency of those techniques.

1.2 Report Structure

The technical results of the work performed during this contract period are presented in three sections. Section two contains software technique design and analysis for the eighteen software techniques studied. Presentation of each technique includes a flow diagram and a description of the technique. Also, an analysis of its capabilities and limitations, related existing software, and estimated run times are provided to assist NASA planners in preparing for the implementation of similar operational systems. Section three discusses the hardware implications of implementing the image processing software on conventional computer configurations, and section four presents some of the general observations and conclusions made by the task team during the period of the project performance.

SECTION 2. SOFTWARE TECHNIQUE ANALYSIS

The technical design effort for Space Station experiment (FPE 5.3A) is presently in its preliminary stage, and since a more in-depth definition of the experiment apparatus and operations was needed, the project team decided to base this work on an advanced project where detailed design information was more readily available. Therefore, an experiment from the Skylab program, the Apollo Telescope Mount Experiment S-056, was chosen because it bore a close resemblance to the subject Space Station experiment and detailed design information about S-056 was readily available. Consequently, the software techniques which are discussed in the following pages refer with equal ease to a Skylab program experiment and to a Space Station experiment.

The image data processing techniques studied by this project are designed to provide the experimenter in space a real-time image processing capacity and a capability for preparing and presenting decision-oriented displays. By accomplishing the data processing needed for such decision-oriented displays in space, real-time communications requirements for the monitoring and control of the experiment can be drastically reduced. Since it is necessary to eliminate as much noise as possible from the experiment data before it is analyzed, many of the techniques discussed in this report deal with the problems of noise removal and distortion correction.

The image processing techniques of this report have been broken into three categories--enhancement, restoration, and manipulation. Each of these categories are further broken into groups of related techniques. Figure 2-1 presents the logical relation of the image processing techniques under their appropriate groupings and classifications.

Each of the image processing techniques examined in this report is presented under the following outline:

IMAGE DATA PROCESSING			
	Classification	Technique Name	Paragraph Ref.
ENHANCEMENT	Point Averaging	Multi-Copy Point Averaging	2.1.1.1
	Spatial Calculus	Spatial Integration	2.1.2.1
		Spatial Differentiation	2.1.2.2
	Gray Scale Alterations	Position Invariant Alterations	2.1.3.1
		Position Dependent Alterations	2.1.3.2
		Gray Scale Limiting	2.1.3.3
RESTORATION	Inverse Filter Processes	Space/Frequency Conversion	2.2.1.1
		Convolution	2.2.1.2
		Deconvolution	2.2.1.3
	Interpolations	Interpolation Path Reduction	2.2.2.1
		Data Interpolation	2.2.2.2
MANIPULATION	Geometric Manipulations	Geometric Distortion Correction	2.3.1.1
		Aspect Ratio Correction	2.3.1.2
		Frame Rotation	2.3.1.3
		Boundary Tracing	2.3.1.4
	Photometry	Area Calculation	2.3.2.1
		Centroid Calculation	2.3.2.2
		Common Feature Association	2.3.2.3

Figure 2-1. Classification of Image Processing Techniques

- Title
- Purpose
- Operations Involved
- Input and Output
- Flow Diagram (with terms used)
- Capabilities and Limitations
- Related Off-the-Shelf Software
- Estimated Run Time

An attempt has been made to make the treatment of each technique more-or-less self-sufficient so that the reader is not forced to refer to other portions of this document when considering a specific technique. A few general considerations, however, should be kept in mind.

The purpose stated for each technique is its justification with respect to a single specific space experiment. There may very well be other equally useful applications of the technique in image data processing.

The discussion of technique Operation and the associated Flow Diagrams are presented at a level sufficient to describe the method used to accomplish a specific image processing task. It is not intended that this report present an operational software design for the system.

The discussion of technique Capabilities and Limitations applies only to a specific application. It is the product of the thinking of the task team during the performance of this contract and in that sense represents an opinion as to the usefulness of the technique in accomplishing its stated purpose.

Related Off-the-Shelf Software has been very difficult to assess. Very little in-depth documentation was obtained during the project period and consequently, the discovery of related and usable software may not be complete.

Estimated Run Times are based on the time that would be required to process a picture of 512x512 picture elements, each element requiring 6 bits which accommodates 64 levels of gray. Since the hardware configuration of Space Station is unknown, the processor used as the basis for the run time estimates was the IBM 7094. It is felt that an estimated run time on a machine as well known as a 7094 will have more meaning than an attempted estimate for a far less familiar hardware configuration. Also, since some preliminary, programming and test was accomplished during the project, the estimates provided for 7094 run times are more accurate than could be provided for another machine.

2.1 Image Enhancement

Image enhancement operations are those processes which are used to improve the quality of an image so that specific data may more easily be retrieved. Such techniques employ relatively simple devices of filtering, and selective amplification. Three classes of image enhancement are addressed:

- Point Averaging
- Spatial Calculus
- Gray Scale Alterations

2.1.1 Point Averaging. Electronic noise introduced into a digitized picture in a random manner can be detected by comparing the gray scale value of corresponding picture elements of multiple scans of the same image. Scan values which differ from the average by more than a specific amount can then be removed and a new average calculated. This process is referred to as Multi-copy Point Averaging.

2.1.1.1 Multi-Copy Point Averaging

Purpose. When a photographic image is scanned by an electronic device to produce a digital electronic representation of the image, electronic noise is often introduced which is both additive and random. This technique is used to eliminate random additive electronic scanning noise by averaging a number of scans of an image and discarding values which differ from the average by a significant amount. Because of its random nature, the probability of encountering a noise spike at precisely the same position on several consecutive scans of the same image is remote.

Operations Involved. This technique performs the following:

- At each picture point a number of digitized scans of the picture element are averaged together.
- Each scan of the same picture point is then compared with the average.
- Any scan which differs from the average by more than a specified amount is noted.
- After all scans of the point have been checked against the average, those which are within tolerance are averaged together again to produce the final value for the picture point.

Input and Output. This technique requires a number of scans of the image to be processed (three or more). The scans should be made on a optical scanner under identical conditions and without physically disturbing the position of the film between scans. In addition, a parameter which sets the permissible percentage of point variance from the average point value is required.

Application of this technique produces a single digitized picture from which additive, random electronic noise has been removed. Also, an average gray scale level for each picture line and for the entire frame is provided for use in picture analysis.

Flow Diagram. Figure 2-2 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram.

- I,J - The line number and column number of the element in process
- K - The scan number of the element in process
- E - The input picture data element
- L,C - The number of lines and columns in the frame
- N - The number of scans within acceptable limits
- SKNS - The number of input frame scans used
- SUM - The sum of the scans for one picture point
- LMT - The percentage variation from the average of all scans which is allowable for a picture element to be retained in the final average
- AVG - The calculated average value of all scans which are within the prescribed range of the total average
- LINAV - The average gray scale value for a picture line
- PICAV - The average gray scale value for the entire frame.

Capabilities and Limitations. This technique is effective in eliminating truly random noise, provided several scans are used in the averaging process. The use of the technique to attenuate coherent noise such as AC pickup is of limited value since such pickup may duplicate itself within each scan.

Related Off-the-Shelf Software. The application of this technique is largely dependent on the type of image scanner used. Since the process is very simple, a number of variations on the technique are available. Some scanners, particularly those employing direct computer interface, apply this technique as an integral part of their scanning process. Another method for accomplishing the same purpose is to simply hold the scanning spot over a picture element and obtain a time integration of the gray scale value electronically.

Estimated Run Time. It is estimated that approximately four minutes of CPU time will be required by a 7094 to process one 512x512 point picture.

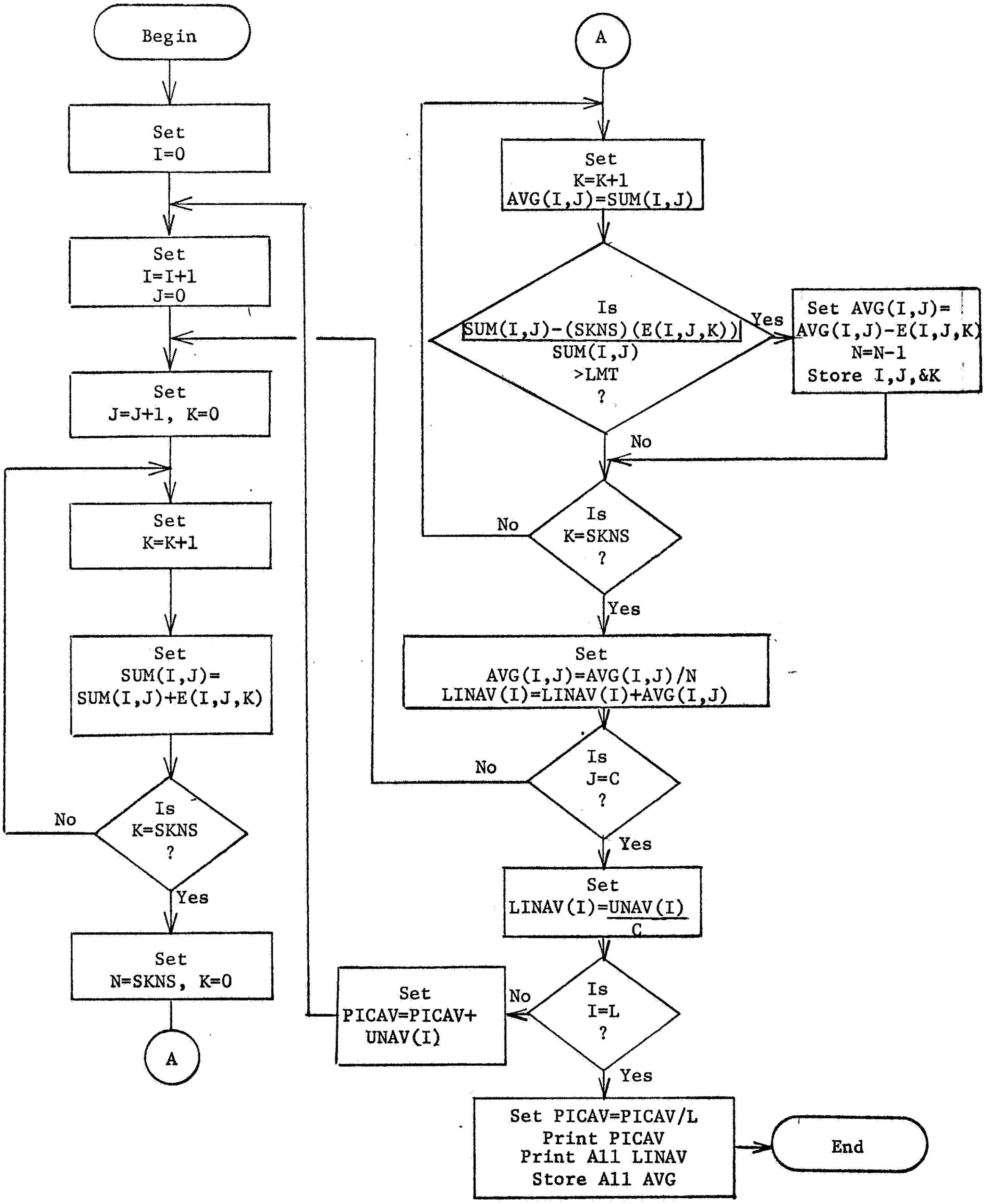


Figure 2-2. Multi-Copy Point Averaging

2.1.2 Spatial Calculus. Two elementary forms of spatial calculus are presented. A simplified spatial integration is used to smooth local irregularities of a scanned picture, and spatial differentiation is used to determine the rate of change of gray scale values over a picture frame and to determine the direction of maximum density gradient.

2.1.2.1 Spatial Integration

Purpose. As it is applied to image enhancement, spatial integration is used to filter or smooth the image. This usually involves an averaging of each picture element with its neighbors. The purpose of this technique is to remove the effects of film grain noise without appreciably diminishing useful high frequency data content.

Operations Involved. This technique performs a spatial integration of an eight element area and adjusts the picture element in the center of that area as follows:

- An average value for a picture element and the eight picture elements which surround it is computed.
- The center element is compared to this average.
- If the center element differs from the average by more than a specified amount, it is modified to a value which is within an acceptable range of the average.

Input and Output. In addition to the subject digitized image, two control factors must be specified--a value (LMT) within which an element may differ from the average of its neighbors, and a factor (ASST) by which the amount of correction applied to an out-of-limits element is controlled.

Application of this technique produces an image which has had all picture elements tested and adjusted to ensure a specified level of similarity with their neighboring elements.

Flow Diagram. Figure 2-3 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram.

- I,J - The line number and column number of the element in process
- E - The input picture data element
- A - The output picture data element
- L,C - The number of lines and columns in the picture
- LMT - The percentage of variance allowed between an element and the average of its neighboring elements
- AJST - The percentage of the difference between a picture element and the average of its neighbors by which an out-of-limits element is modified.

Capabilities and Limitations. This operator performs a very limited form of spatial integration. It will, however, reduce the overall spatial gradient of the picture. Therefore, it should not be applied before edge detection or differential techniques for measurement of density gradient.

Related Off-the-Shelf Software. Various techniques of spatial integration are used for "filtering" by most image processing facilities. A notch filter of 21x41 picture elements is used at JPL for removal of television scan line noise.[2] The use of off-the-shelf packages for this technique should be preceded by a careful examination of the picture origin and the processes which are to be applied for subsequent analysis, since this technique produces what is essentially an out-of-focus image.

Estimated Run Time. It is estimated that this technique will require approximately three minutes of 7094 time to process a single 512x512 picture.

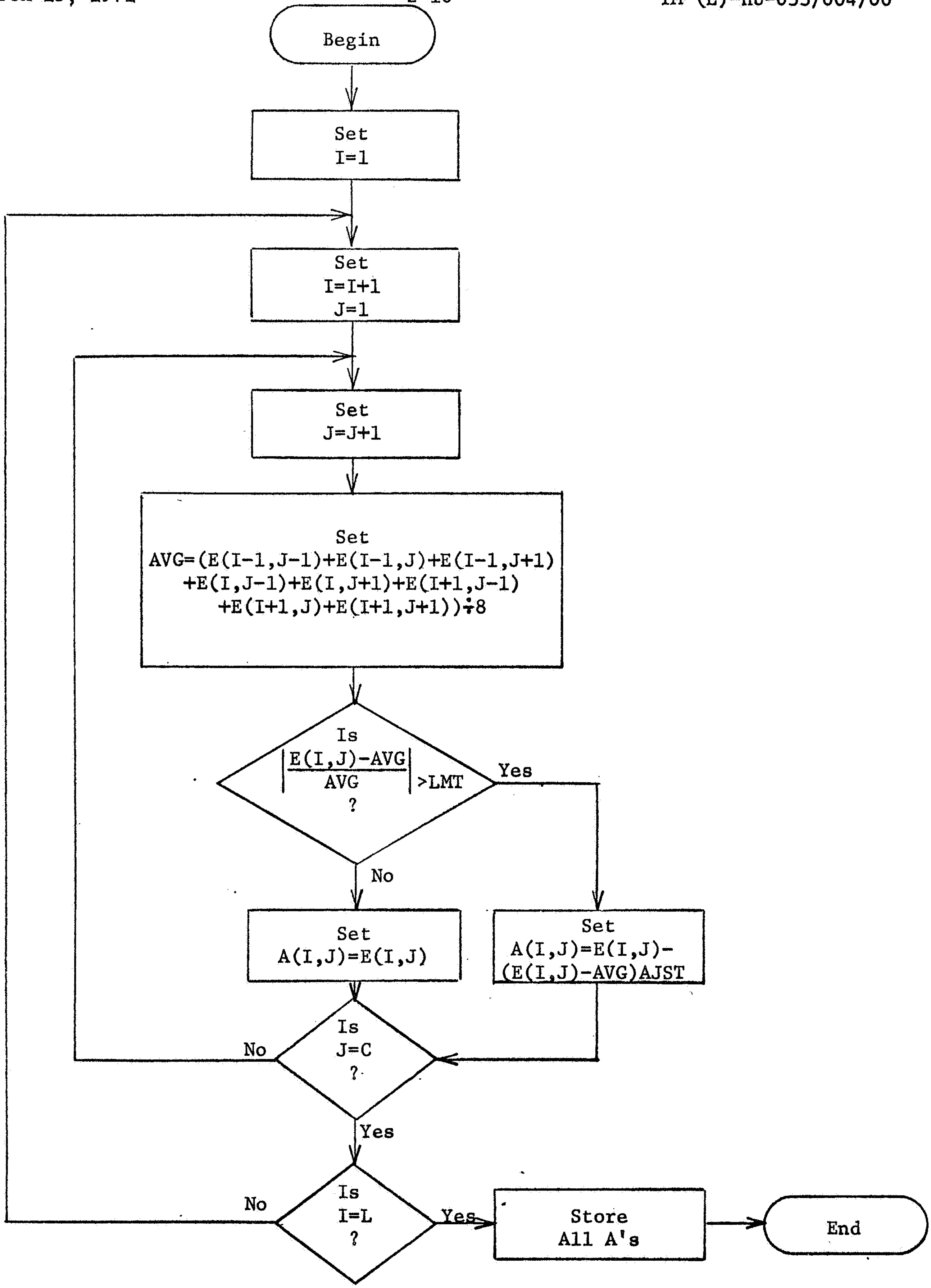


Figure 2-3. Spatial Integration

2.1.2.2 Spatial Differentiation

Purpose. The purpose of this technique is to determine the spatial derivative and the direction of maximum gradient for each picture element of an image. Its use is varied. It may be used to determine data points which are contributed to the image by trash, scratches, or other pictorial anomalies, or it may be used as the reverse of spatial smoothing to sharpen the picture and heighten edge definition.

Operations Involved. This technique performs the following:

- A numerical differentiation process is employed to determine the element to element rate of gray scale change in the vertical and horizontal directions.
- The angle of the gradient vector and the magnitude of the gradient are then calculated.
- Using the convention that gray scale change from low to higher density is a positive change, the polar quadrant to be assigned to the gradient angle is determined.

Input and Output. The only input data required for this operator is the digitized picture upon which the spatial differentiation operation is to be performed.

Spatial Differentiation produces an image with gray scale values which correspond to the magnitude of the spatial gradient and angles which define the direction of that gradient at each picture point. Both values may be represented by six bit binary numbers. The first corresponding to gray scale and the second to the angle of the gradient between 0-360° in 6° steps.

Flow Diagram. Figure 2-4 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram.

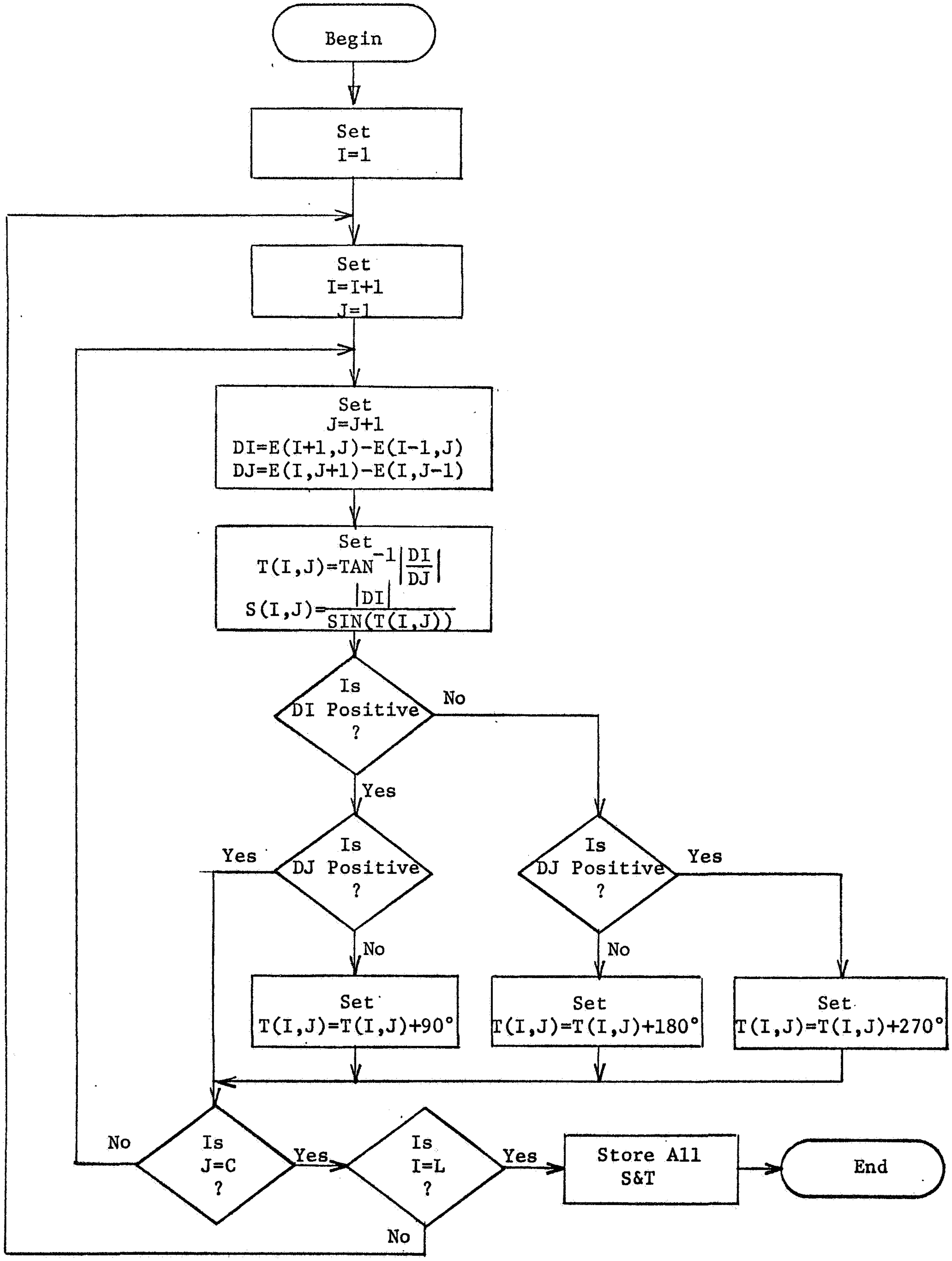


Figure 2-4. Spatial Differentiation

I,J - The line and column number of the element in process

DI,DJ - Are the directional derivatives of the image along the lines and columns

T - The angle of maximum gray scale gradient

S - The gray scale value of the maximum gradient

L,C - The number of lines and columns in the picture.

Capabilities and Limitations. Care must be exercised in applying Spatial Differentiation to an image. It will produce an image which has maximum density where there were edges or gray level changes in the original picture and completely "wash out" large areas of constant gray level--no matter what the original gray value of the area. Since the gray scale which results from this operator is always less contrasty than the original picture, it may require contrast stretch or other operations before it can be successfully utilized.

Related Off-the-Shelf Software. Theoretically, spatial differentiation should restore a picture which has been blurred by an integration process. In practice, however, it appears that techniques of spatial high-pass frequency filtering are preferred for such purposes. No practical application of spatial differentiation for the purpose of image enhancement was found during this study. It is included so that it can be specified for use in conjunction with another technique where "edge detection" is required.

Estimated Run Time. Because this technique must have access to picture elements in both vertical and horizontal directions, the use of a high speed random access memory is highly desirable. It is estimated that two minutes of 7094 time will be required for processing a single 512x512 picture with this technique.

2.1.3 Gray Scale Alterations. Techniques for manipulating the range and level of densities of an image represent the oldest form of image enhancement. Ideally, the density variation of a filmed image takes place over the linear portion of the D log E film characteristics curve. Because of a number of possible variations in the optical system, portions or all of a picture frame may be shifted into the low or the high density end of the film curve causing a loss of shadow or highlight detail.[3] Three techniques for gray scale alterations are presented--Position Invariant Alterations, Position Dependent Alterations, and Gray Scale Limiting.

2.1.3.1 Position Invariant Gray Scale Alteration

Purpose. This technique can be used wherever it is desirable to modify image gray scale values uniformly over the entire frame. Specifically, the following operations may be performed: Contrast Stretch, Film Curve Corrections, and Uniform Density Shifts.

Operations Involved. This technique scans an image frame, a line at a time, picture element by picture element and performs the following:

- Reads the gray scale value of each element scanned.
- Withdraws a modified gray value from a gray scale alteration look-up table.
- Produces a new picture frame with gray values modified in accordance with the look-up table.

Input and Output. In addition to the digitized subject image, a gray scale alteration table must be provided which consists of a series of numbers corresponding to gray scale values for each picture element in the image. Each number corresponds to an input gray value in the image, and the number itself is the value to which that input gray value is altered. The tables range of values should correspond to the number of gray levels in which the image is quantified. The output from this operator is a digitized image whose gray scale values have been modified in accordance with the alteration table.

Flow Diagram. Figure 2-5 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram:

- I,J - The line and column number of the picture element in process
- TABLE - Contains the gray scale values which are substituted for the original gray values to perform the desired image alteration
- L,C - The number of lines and columns in the image frame
- E - An input picture data element
- A - An output picture data element.

Capabilities and Limitations. This technique is an extremely flexible tool for the improvement of images which have been degraded by a process which shifts the operating density range of the image on the film density curve, such as incorrect exposure. Because a look-up table is used to control the modification process, rather complex changes can be made in the film density distribution.

Care must be taken not to exceed the number of gray levels to which the input picture was originally quantified. That is, if six bits (64 levels) were alloted to each picture element for gray scale designation in the original picture, no more than 64 levels of gray are allowed in the output picture.

Related Off-the-Shelf Software. Gray scale alteration by table look-up is such a basic tool for image processing that virtually any image processing system possesses its capability. There are many variations on the method for generating the alteration function but they generally employ some form of table look-up technique.

Estimated Run Time. It is estimated that approximately one and one-half minutes of 7094 time will be required to process a single 512x512 point picture with this technique.

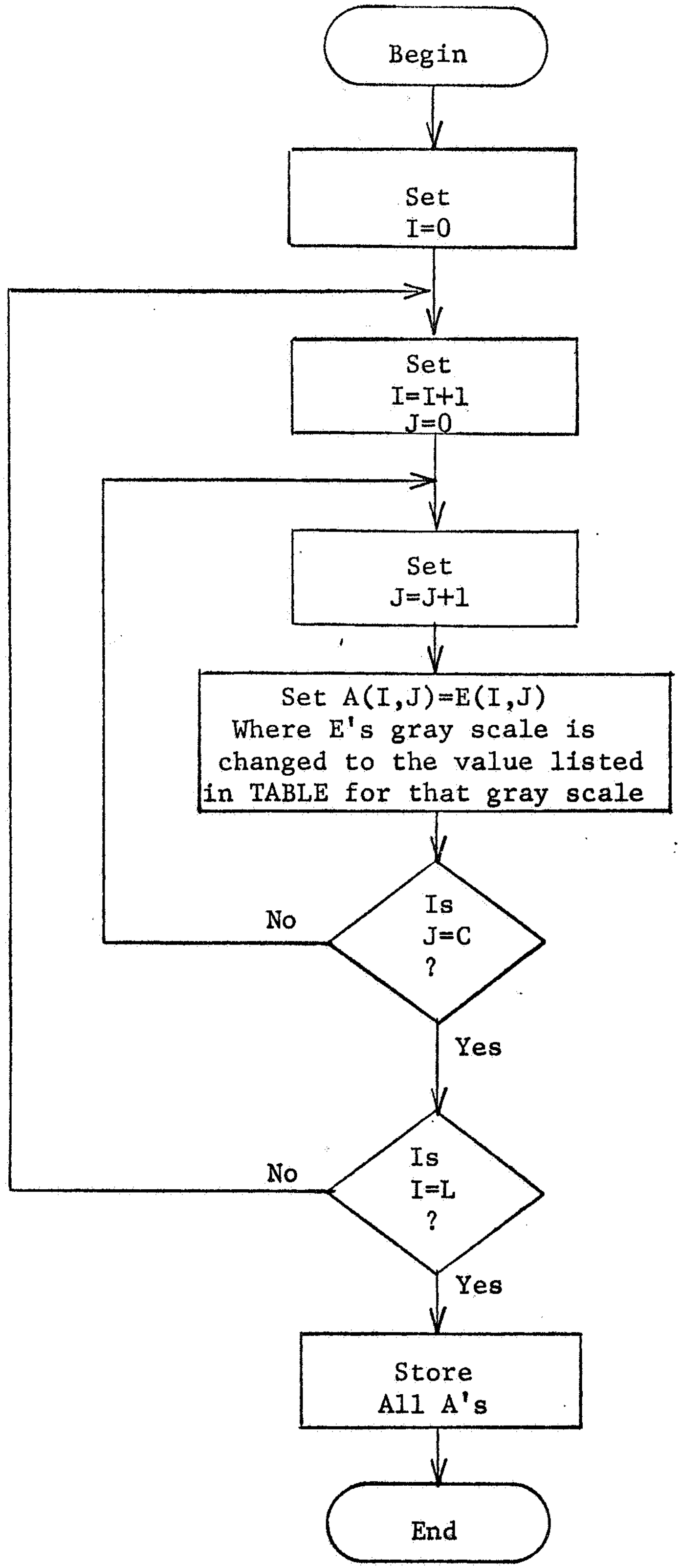


Figure 2-5. Position Invariant Gray Scale Alterations

2.1.3.2 Position Dependent Gray Scale Alteration

Purpose. This technique is used when picture element gray values must be modified as a function of the radial distance from the center of the frame. The technique is designed to offset the vignetting effect of imperfect optics. However, it can be used to simultaneously correct such vignetting and to modify the entire frame gray scale by a linear expression at the same time.

Operations Involved. This technique scans an image frame, a line at a time, picture element by picture element and performs the following:

- Calculates the distance (R) between the picture element and the center of the field of view.
- Withdraws a modification factor, corresponding to the distance (R), from a look-up table.
- Applies the modification factor to the picture element to alter the picture element gray scale value.
- Produces a new picture frame with gray values modified in accordance with the look-up table.

Input and Output. In addition to the digitized subject image, a gray scale alteration table which consists of a series of pairs of numbers for each picture element in the image must be provided. Each number pair corresponds to some distance R from the center of the frame. The number pair are the coefficients (a and b) of the linear expression a+bx. In operation, the gray scale value for a picture element is substituted into the expression for x with coefficients a and b taken from the alteration table corresponding to R. The output from this operator is the digitized image modified by the alteration table coefficients.

Flow Diagram. Figure 2-6 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram.

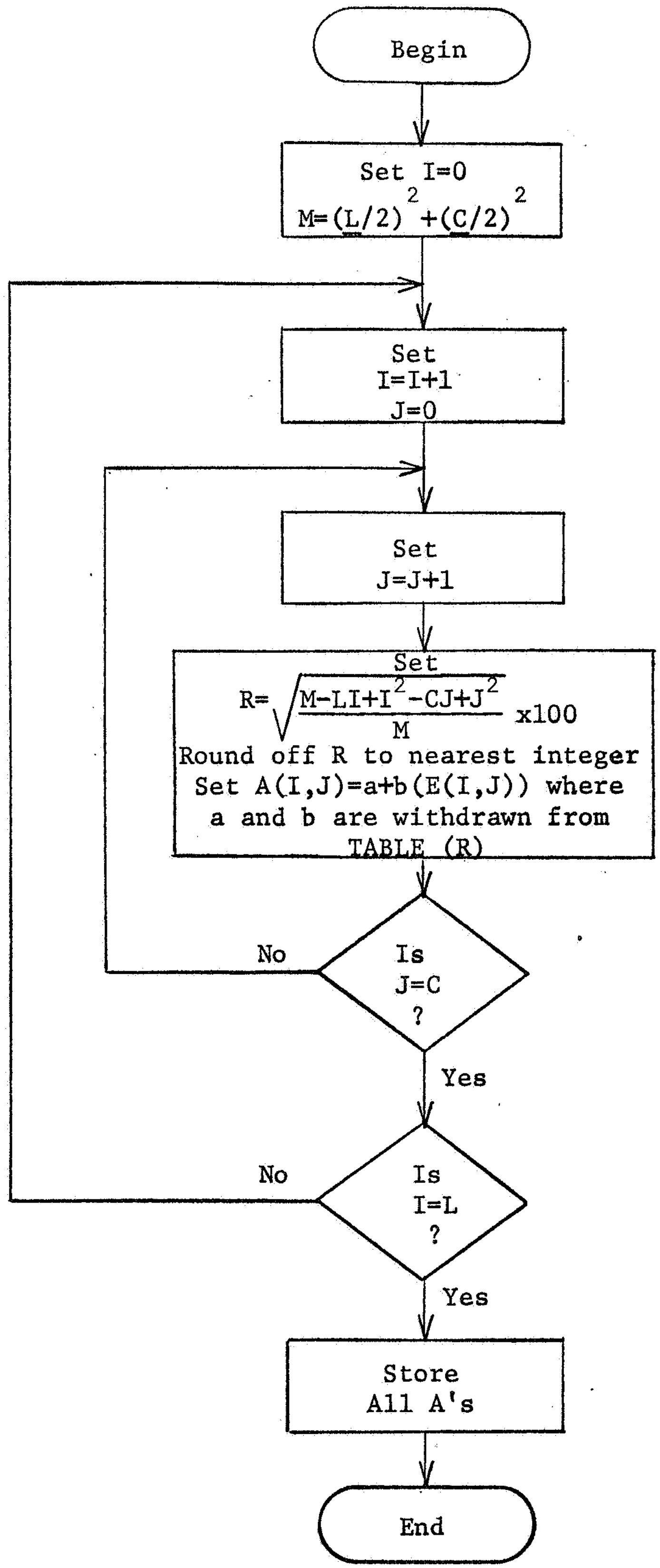


Figure 2-6. Position Dependent Gray Scale Alteration

I,J - The line and column number of the picture element in process

E - An input picture data element

A - An output picture data element

TABLE - Contains the number pairs for each picture element. The values of the numbers for each picture element are dependent on the element's distance from the center of the frame. Each number pair represents the coefficients (a and b) to a linear modifier of the form a+b(x)

L,C - The largest numbered line and column in the image frame

$\underline{L}$,$\underline{C}$ - The number of lines and columns, in the entire, original image frame. (This does not correspond to L and C when less than a full frame is being processed.)

Capabilities and Limitations. This technique is useful in performing alterations of picture gray scale where those alterations can be expressed as a linear function of picture element position with respect to the central point of the frame. The form of look-up table modifier used in this operator allows for gray scale translation as well as expansion or contraction.

Because the alterations that can be performed on each picture element are limited to that of a first order equation, they are more restricted than gray scale alterations performed under the position invariant operator.

Related Off-the-Shelf Software. A number of position dependent gray scale alteration routines are available off-the-shelf. However, the technique most often used is to simply provide a look-up correction factor for each picture element position. This gives greater flexibility but requires considerably more input/output time.

Estimated Run Time. It is estimated that this technique will require approximately two minutes of 7094 time to process a single 512x512 element picture.

2.1.3.3 Gray Scale Limiting

Purpose. The purpose of this technique is to isolate those portions of a picture which are within a specific range or band of gray scale values. Because film density is relatable to X-ray intensity, density band pass operations may be used to produce a picture of those portions of the sun producing photons at specific rates.

Operations Involved. This technique performs the following operations:

- Each picture element is scanned to determine if its gray scale value is within upper and lower prespecified limits.
- If it is low, the gray scale value for that element is set to (B).
- If it is high, its gray scale value is set to (T).
- If it is within the limits, a counter is incremented by one, and the gray value is left unchanged.

The total in the computer when the entire frame has been scanned can be related to the solar surface area within a specific energy level range.

Input and Output. In addition to the digitized image of the solar X-ray emissions, upper and lower gray scale limits must be specified. Gray scale values to which picture elements which are outside of those limits are set, are also required.

These operations provide a tally of the number of picture elements which have gray values within specified levels and create a new picture with all elements outside of those levels set to a prespecified gray value.

Flow Diagram. Figure 2-7 presents a general flow diagram of this enhancement technique. The following is a definition of the terms used in that diagram.

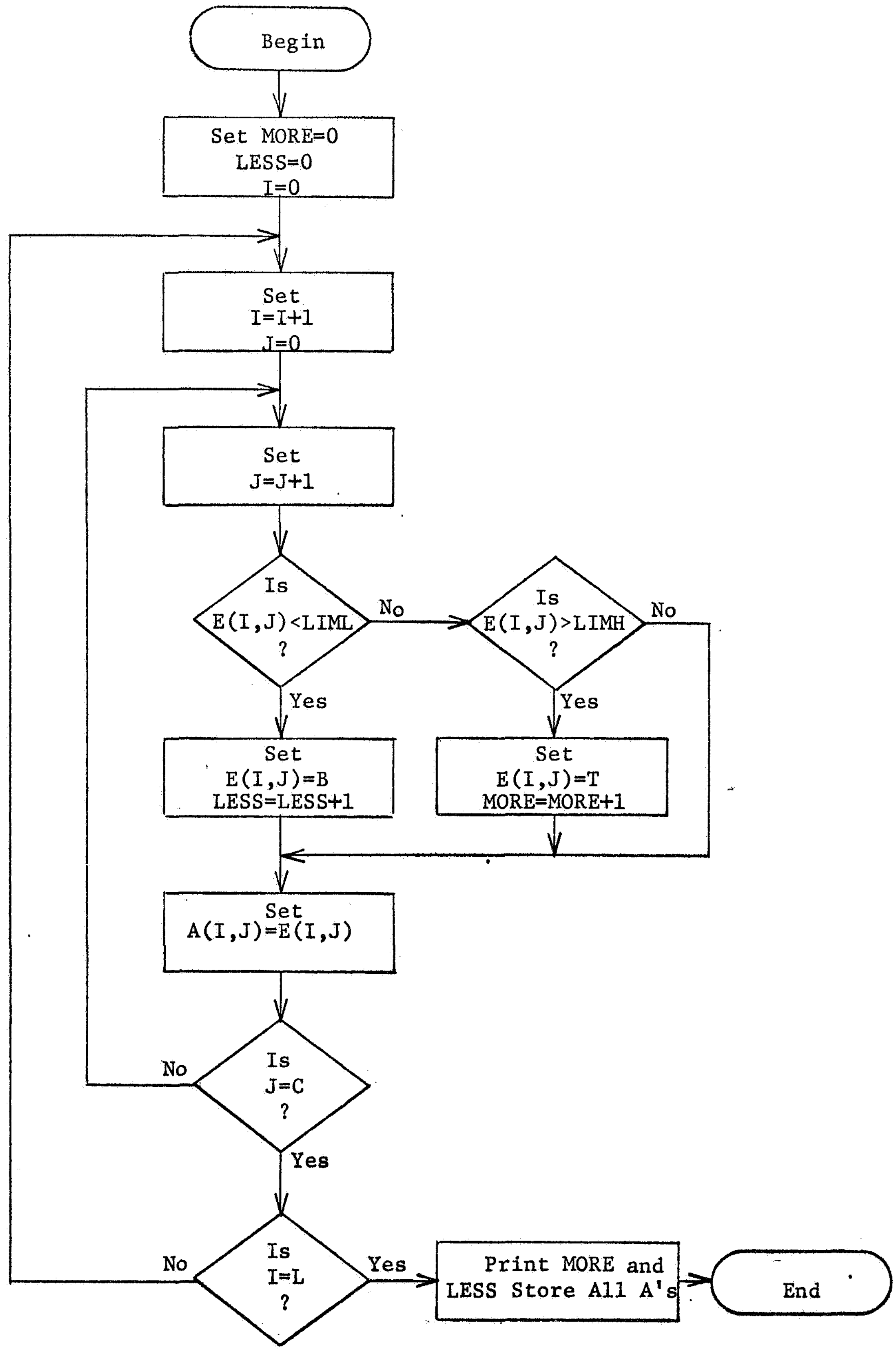


Figure 2-7. Gray Scale Limiting

LIML - The gray scale value which is the lowest value acceptable for inclusion in the output picture without alteration

LIMH - The gray scale value which is the highest value acceptable for inclusion in the output picture without alteration

B - The gray scale value to which all picture elements which exceed the lower limit (LIML) are set

T - The gray scale value to which all picture elements which exceed the upper limit (LIMH) are set

MORE - A tally of the number of picture elements which exceed (LIMH) and are set to (T)

LESS - A tally of the number of picture elements which exceed (LIML) and are set to (B)

L,C - Designates the number of lines and columns in the subject picture frame

E - Designates an input picture data element

A - Designates output picture data element

I,J - Designates the line and column number of the picture element in process.

Capabilities and Limitations. This technique is relatively foolproof provided the user does not try to use it for more sophisticated purposes than for which it was intended. Care should be taken in selecting the values of LIM since the gray scale values of the picture may vary as a function of position as well as flux density.

Related Off-the-Shelf Software. The thresholding of certain bands of picture density is an integral part of numerous available software packages. For instance, JPL uses a program called "Black and White Copy" which is essentially a variation of the gray scale limiting technique with LIML and LIMH set to the same intermediate level, (B) set to zero, and (T) set to maximum density.

Estimated Run Time. It is estimated that this technique will require approximately one and one-half minutes to process a single 512x512 element picture.

2.2 Image Restoration

The techniques used to restore a degraded image employ various mathematical processes to reproduce those portions of the image data which are seemingly lost. In some cases, the resultant image may only be a best "statistical" guess as to what the original data may have been. Although no amount of enhancement can retrieve image data that is truly lost, estimates of the original data frame can be made using the data that remains, and techniques such as inverse filtering and interpolation. Image processes which employ techniques such as inverse filtering and interpolation are classified as image restoration techniques.

2.2.1 Inverse Filter Processes. Some of the most potentially useful tools for image restoration are the techniques of inverse filtering or deconvolution Recently, such techniques have been very successfully employed in restoring pictures taken during the moon surveyor program. Several approaches may be used, but a few mathematical processes are basic to inverse filter image restoration--Space/Frequency Conversion, Convolution, Deconvolution.

2.2.1.1 Space/Frequency Domain Conversion

Purpose. A number of factors make it desirable to translate picture data from the spatial displacement domain into the spatial frequency domain. Perhaps the most important of these is simply the ability to characterize the linear image in space as a series of continuous sinusoidal waveforms. If the point spread function (PSF) of an optical system is scanned, digitized, and converted to the frequency domain, the resultant spatial frequency spectrum is analogous to the modulation transfer function (MTF) of an electrical network. The overall effect of the PSF is to reduce the spatial frequency bandwidth of the system, as evidenced by the high frequency roll-off of the spatial MTF. By applying various compensating techniques to broaden the frequency response of the system in the frequency domain, it is possible to significantly improve overall picture quality in the spatial domain.[4]

Two theorems also contribute to the desirability of being able to convert a picture into the frequency domain. One states that if f(x) exists in the frequency domain as F(s) and g(x) exists in the frequency domain as G(s), then the convolution of f(x) with g(x) equals the product F(s)G(s) converted back into the space domain. Another theorem states that if a spatial function f(x) exists in the frequency domain as F(s) then its auto-correlation function is $[F(s)]^2$ converted back into the space domain.

These and other useful applications make the ability to transform picture data from space to frequency domain and vice versa an extremely useful tool in image data processing. The purpose of this technique, then, is to prepare an image data frame for conversion, and apply a fast Fourier transform algorithm to the data frame, converting it from one domain to the other.

Operations Involved. The space/frequency domain conversion technique of this operator is based on the Cooley-Tukey Fast Fourier Transform (FFT) algorithm. This algorithm is derived from the theorem that periodic functions can be expanded in series form in terms of harmonically related sinusoids as:

$$F(\ell) = a_o + \sum_{n=1}^{\infty} (a_n \text{Cos } n2\pi f\ell + b_n \text{ Sin } n2\pi f\ell)$$

By applying Enler's equation

$$e^{\pm j2\pi f\ell} = \text{Cos } 2\pi f\ell \pm j \text{ Sin } 2\pi f\ell \qquad (j=\sqrt{-1})$$

The expression can be transformed to an exponential form

$$F(\ell) = \sum_{n=-\infty}^{+\infty} C_n e^{j2\pi f\ell}$$

$$\text{where} \quad C_n = \frac{1}{L} \int_{-L/2}^{+L/2} f(\ell)\, e^{-jn2\pi f\ell}\, d\ell \qquad (T=1/f)$$

is the complex Fourier coefficient.

By substituting the expression for Cn into the expression for $F(\ell)$ we obtain

$$F(\ell) = \sum_{n=-\infty}^{+\infty} [1/L \int_{-L/2}^{+L/2} f(\ell)\ e^{-j2\pi f\ell n} dl]e^{j2\pi f\ell}$$

which can be simplified to

$$F(\ell) = \int_{-\infty}^{+\infty}[1/L \int_{-\infty}^{+\infty} f(\ell)\ e^{-j2\pi f\ell}\ d\ell]e^{j2\pi f\ell}\ df$$

This yields the Fourier transform pair:

$$S(f) = 1/L \int_{-\infty}^{+\infty} f(\ell)e^{-j2\pi f\ell}\ d\ell$$

$$F(\ell) = \int_{-\infty}^{+\infty} S(f)e^{j2\pi f\ell}\ df$$

Since it is desirable to compute the Fourier transform with a digital machine, only a finite number of discrete samples of both space and frequency can be considered. If the picture line to be transformed is digitized to N samples and each sample has a spatial dimension of ΔL, then the spatial period $1/\Delta L$ must contain complete information of the frequency spectrum of the picture line, and a discrete form of the expression for $f(\ell)$ can be derived.[5] If we set $\ell_k = K\Delta L$, $fn = n\Delta f$ and note that $\Delta L = L/N$ and $\Delta f = 1/L$ (L is the spatial length of a picture line, we arrive at the expression

$$S(f) = \Delta L \sum_{k=0}^{n-1} f(\ell_k)e^{-j2\pi(nk)/N} \qquad n=0,1,2...,N-1.$$

It can be observed that picture gray scale information is contained in $f(\ell)$ and that by setting $e^{-j2\pi/N} = W$ the expression can be reduced to

$$S(f) = \Delta L \sum_{k=0}^{n-1} [W^{nk}][f(\ell k)] \qquad n=0,1,2,...,N-1.$$

If, for example, we choose the number of sample points N = 4 we arrive at an array

$$\begin{bmatrix} S(0) \\ S(1) \\ S(2) \\ S(3) \end{bmatrix} = \begin{bmatrix} W^0 & W^0 & W^0 & W^0 \\ W^0 & W^1 & W^2 & W^3 \\ W^0 & W^2 & W^4 & W^6 \\ W^0 & W^3 & W^6 & W^9 \end{bmatrix} \begin{bmatrix} f(1_0) \\ f(1_1) \\ f(1_2) \\ f(1_3) \end{bmatrix}$$

Straightforward computation of this array would require $16(n^2)$ complex multiplications and additions. The FFT algorithm is a fast method of performing these complex multiplications and additions by factoring the matrix array in such a way as to minimize the required complex arithmetic. The factoring process is too involved to be included in this work. However, its complexity is justified when it is noted that for N = 1024 a computational reduction of more than 200 to 1 is realized.[6]

Input and Output. The input data required for this technique is a digitized picture of NxN elements where N is an even power of two.

The technique will generate two numbers for each of N frequency terms for each line of the picture. That is, it will generate NxN real frequency coefficients and NxN imaginary or complex frequency coefficients.

Flow Diagram. Figure 2-8 presents a general flow diagram of this restoration technique. The following is a definition of the terms used in that diagram.

- I,J - The line and column number of the picture element in process. (The integer variable J should not be confused with the complex operator $j = \sqrt{-1}$.
- S(nI) - The complex coefficient of $e^{+j2\pi nk/N}$ which contains the real and complex amplitude of the exponential at frequency (n) for picture line (I).
- L,C - The number of lines and columns in the picture
- X(k) - The sampled spatial function which describes gray scale value as a function of displacement (KΔN) along the picture line.

Capabilities and Limitations. This technique provides a complex analysis of the one-dimensional frequency spectrum of a picture frame. The lowest frequency

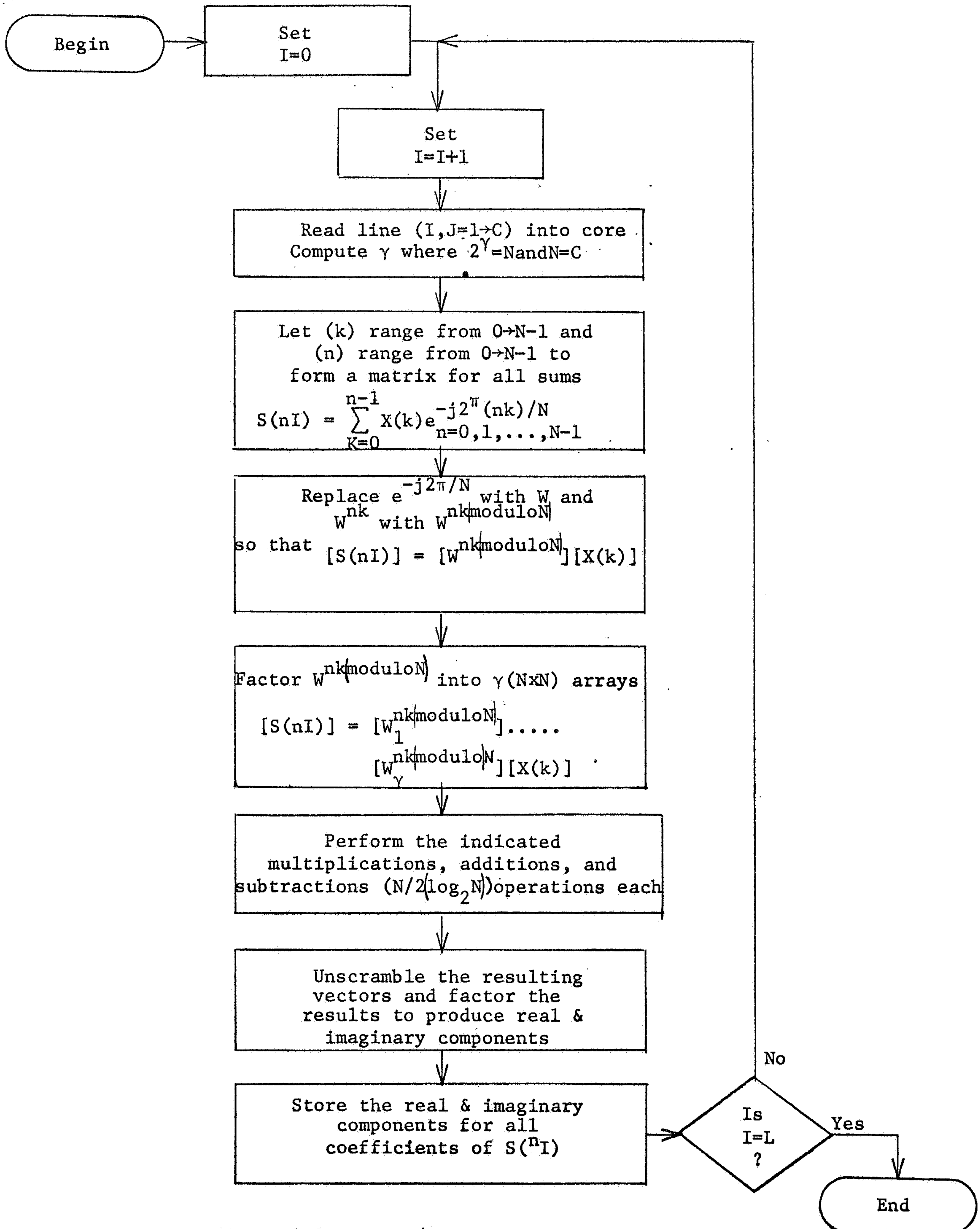


Figure 2-8. Space/Frequency Domain Conversion

evaluated is the DC component while the highest equals N/2 where N is the number of samples per picture line. This may exceed the resolution capabilities of the film, making the higher frequency terms almost wholly functions of noise. Since picture operations are inherently two-dimensional, a one-dimensional frequency analysis is of questionable value to image data processing. The one-dimensional process does, however, indicate the basis for the development of fast Fourier operators and thus serves the purposes of this report.

Related Off-the-Shelf Software. The Fast Fourier Transform is a commonly used software tool. A number of variations of the original Cooley-Tukey algorithm are presently available. Operational routines for both one and two-dimensional transforms are available to the MSFC Computation Laboratory.

Estimated Run Time. It is estimated that this technique will require approximately four and one-half minutes of 7094 time to transform a single frame of 512x512 elements into one dimension.

2.2.1.2 Convolution

Purpose. A large number of image data processing operations rely on the convolution of the image with another spatial function. The "Spatial Integration" technique is a special form of such a convolution. Numerous techniques for frequency component improvement make use of convolution to apply a filter to an image. By constructing such a filter as an approximate inverse of the spread function of the generating system, spatial frequency response can be significantly improved.

The purpose of this technique is to convolve an image frame of LxC points with a filter frame of 2a+1, 2b+1 points in two dimensions.

Operations Involved. The operations involved in this technique effectively multiply each picture point of the image by all of the matrix points of the filter and the resulting arrays, thus produced, are added together where they spatially overlap. Mathematically this is equivalent to

$$G(I,J) = \sum_{-a}^{+a} \sum_{-b}^{+b} E(I-y,J-x)\ F(x,y) \text{ where } \begin{matrix} I = 1 \rightarrow L \\ J = 1 \rightarrow C \end{matrix}$$

Input and Output. Data is supplied to this technique primarily in two, two-dimensional arrays. The first is the filter array ((F(x,y)) which contains (2a+1)x(2b+1) values (note that F always has an odd number of x and y coordinates). The second array is the image to be convolved. It contains LxC values and is stored in core in a space which is dimensioned to hold (2a+1)x(C+2a) values. Zeros must be added to all four sides of the image array [making it contain (L+2a)x(C+2a) values] in order to handle convolution at the edges.

The output is an image of LxC picture elements which has been convolved in two dimensions with the filter function F(x,y).

Flow Diagram. Figure 2-9 presents a general flow diagram of this restoration technique. The following is a definition of the terms used in that diagram.

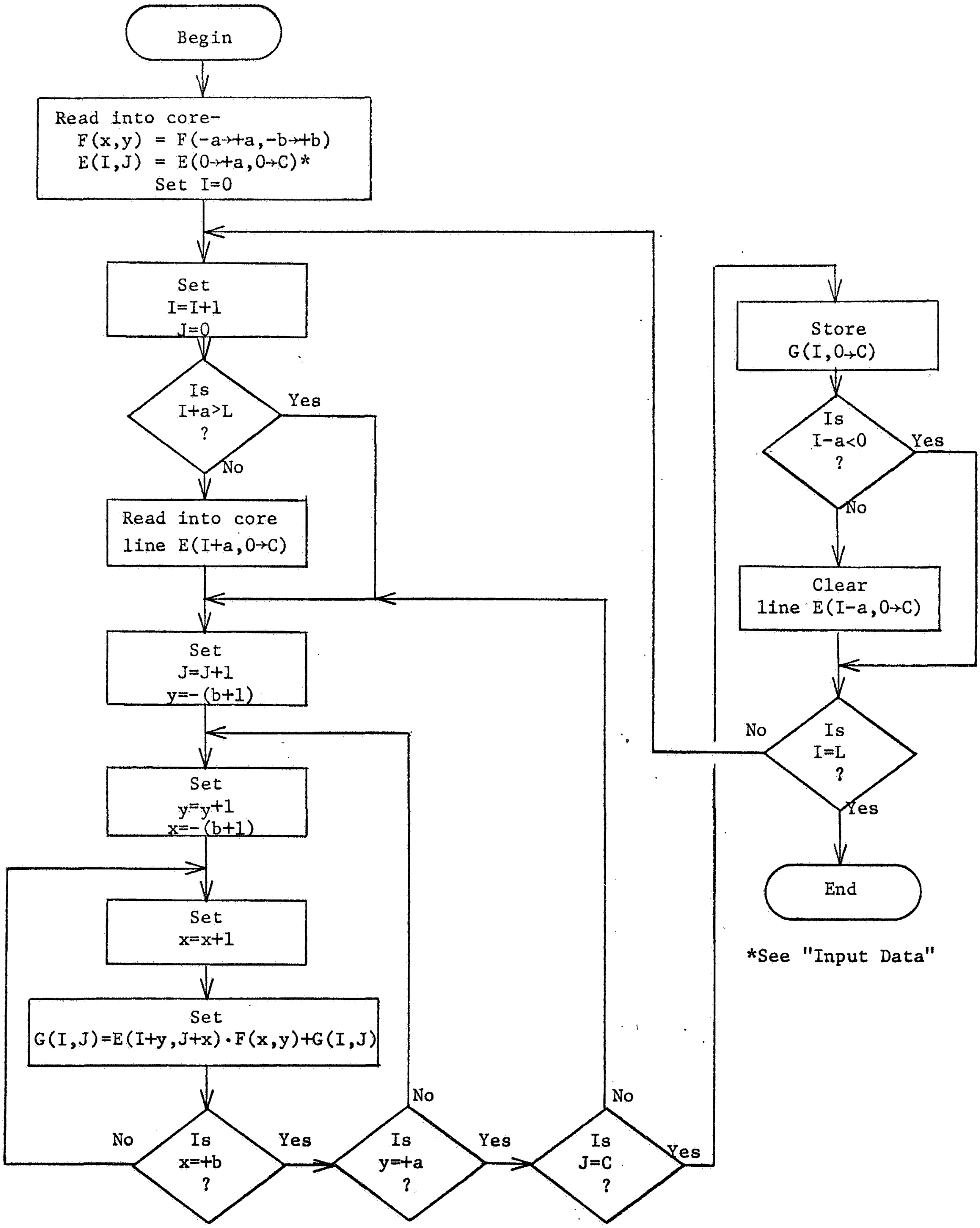


Figure 2-9. Convolution

- E(I,J) - The original digitized picture elements
- F(x,y) - The function to be convolved with F
- A(I,J) - The convolved picture elements produced by this technique
- I,J - The vertical and horizontal designators for the picture elements
- x,y - The vertical and horizontal designator for the filter function elements
- L,C - The number of lines and columns contained in the picture picture frame
- a,b - The number of horizontal and vertical elements in the filter function where the number of vertical elements equals (2a+1) and the number of horizontal elements equals (2b+1). Graphically the filter function may be depicted:

$$F(x,y) = \begin{vmatrix} (-a,-b) & -a,0 & -a,+b \\ 0,-b & 0,0 & 0,+b \\ +a,-b & +a,0 & +a,+b \end{vmatrix}$$

Capabilities and Limitations. This technique is, perhaps, the most singularly useful of all the available image data processing tools. It can be used to perform numerous inverse filtering operations and complex spatial integration operations. It does, however, require a large amount of core and a large amount of processing time. For instance, the convolution of a 512x512 matrix with a $(37)^2$ array requires better than 20K core. Therefore, when this technique is to be used, care should be taken to limit the size of the arrays to be convolved.

Related Off-the-Shelf Software. Various convolution routines, for both single and two dimensions, are presently available. Because of the number of multiply and add operations that must be performed in this technique, some present systems employing convolution tools utilize a hardware black box as a computer peripheral device in order to reduce the CPU time needed for the math. Care also should be taken if off-the-shelf software is to be used in selecting proper high speed random access memory. An all tape system with limited memory can require a ponderous number of tape transfers.

Estimated Run Time. A conservative estimate of the time required to convolve a 512x512 element picture with a 37x37 element filter function on a 7094 is one hour. This assumes that no hardware multiply/add black box is attached.

2.2.1.3 Deconvolution

Purpose. When a point source of radiation is imaged by a photographic system, it spreads out over some finite area on the photographic film. This picture of a point of radiation by a system characterizes the response of the optical system in much the same way as the response of an electrical network to a unit electrical impulse. Such a point source image is called the point spread function (PSF) of the optical system. If a photographic object is thought of as an array of an infinite number of such point sources of radiation of varying intensity, the photographic image (h(x,y)), formed by an optical system is described as the convolution of the PSF (g(u,v)) with the object function (f(x,y)) where

$$h(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} g(u,v)f(x-u,y-v)du\ dv$$

or in the frequency domain

$$H(x,y) = G(u,v)*F(x,y)$$

The purpose of this operator is to perform the reverse of this process so that, given a photographic image h(x,y) and the PSF of the system, the undistorted image of the original photographic object F(x,y) can be produced.

Operations Involved. This technique first converts the PSF into the frequency domain using the FFT. It then calculates the square root of the power density for each frequency term, inverts the result and compares the inverted term with a gain factor "G". If the inverse of the square root of the power density is greater than G, the real and imaginary components of the frequency term are adjusted to increase the power density for that frequency term. A filter term (Fn) is then prepared for each PSF frequency term. This filter is the inverse of the PSF in the frequency domain, adjusted to limit amplification to a maximum of "G". The filter is then convolved with each line of the object picture in the frequency domain and then reconstituted by inverse Fourier Transform.

Input and Output. This technique requires that a point spread function of the system be supplied. Care should be taken to include as many sample values for the PSF as for a line of the picture. Otherwise, there will not be a 1:1 relationship between the frequency terms of the PSF and the transformed picture line. The number of elements per line and the number of lines in the digitized input picture should be expressable as an even power of two. The gain control factor "G" should be chosen to restrict amplification of all frequency components higher than the spatial frequency response of the system. A value which has been used for similar applications is to make G equal to five.

This technique produces a picture which has had its one-dimensional frequency response characteristics altered in an approximate inverse of the roll-off characteristics of the system. Because of the alterations performed in the frequency domain, gray scale relationships may require shifting, compression, or expansion in order to restore proper nominal density and contrast.

Flow Diagram. Figure 2-10 presents a general flow diagram of this restoration technique. The following is a definition of the terms used in that diagram.

I,J	- The line and column number in process
K	- The spatial sample number of the PSF
G	- The maximum gain allowed for Fn
a,b	- The real and imaginary parts of the complex frequency term S(n)
C	- The square root of the power spectrum density. C is related to a and b by $\sqrt{a^2+b^2}$ at an angle of tan -1(b/a)
Sn	- The complex frequency expression for the image data at frequency n
Fn	- The filter term generated from 1/C as determined for frequency n
E(I,J),A(I,J)	- The input and output picture element values
L,C	- The number of lines and columns in the picture frame.

Capabilities and Limitations. As an operable tool, this technique is greatly limited. This discussion, however, does illustrate the technique of

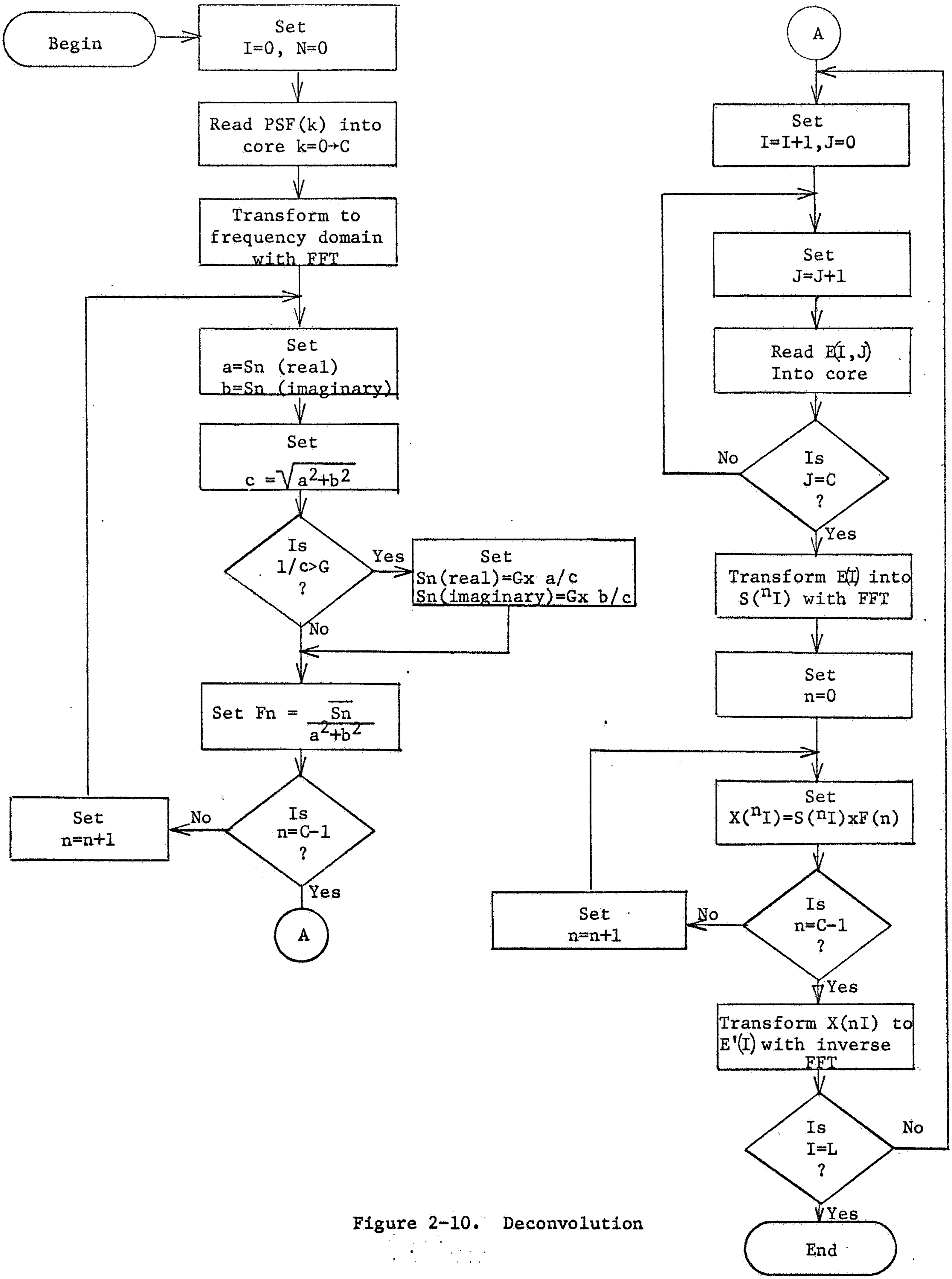


Figure 2-10. Deconvolution

deconvolution of images in one dimension. The reader should be aware that a number of considerations must be taken into account if the technique is to be applied in a practical situation. Some of the more important of these are:

1. The photographic image and the optical PSF are inherently two dimensional. This requires that two-dimension Fourier Transforms be used for all computations instead of the single dimension transforms used in this discussion.

2. The inverse of the PSF in the frequency domain may very well yield indeterminant values which may make recovery of original frequency terms impossible.

3. The PSF for a real system will not likely be position invariant. This will mean the requirement for varying the PSF as a function of its position on the image.

Related Off-the-Shelf Software. Only one working example of the use of direct deconvolution has been discovered by this project.[7] No off-the-shelf software is known to exist which would be applicable to the enhancement of optically degraded X-ray photographs. A variation of this technique, however, is being fruitfully applied to a number of image processing tasks at the University of California's Jet Propulsion Labs. Their technique generates a filter function in the space domain and convolves it with an image by direct convolution processes.

Estimates Run Time. It is estimated that this technique would require approximately ten minutes of 7094 time to process a single 512x512 element picture with a 37x37 element PSF. This time includes the processing required for two Fourier transform operations and one inverse transform.

2.2.2 Interpolations. Because the film that will be used with the solar X-ray telescope is very delicate, scratches and pin holes in the emulsion are quite likely to occur. Such anomalies which are not contributed to the picture by the optical system have no relation to the system point spread function and consequently cannot be removed by any deconvolution process. Attempted deconvolution of film degraded by such noise can easily result in further degradation of the image by replicating each noise point over an area equal to that occupied by the PSF. Since scratches and other such film blemishes are truly lost data, an estimate of the missing picture elements is required by interpolating from data in the surrounding area, if deconvolution techniques are to be employed.

2.2.2.1 Interpolation Path Reduction

Purpose. The purpose of this technique is to determine which is the shortest of two orthogonal paths across a portion of one of the GROUPs produced by the "Common Feature Association" technique (see paragraph 2.3.2.3). The determination of such minimum paths is vital to the interpolation of data where portions of a picture have been lost because of scratches, trash, or other such film blemishes.

Operations Involved. This technique works in conjunction with the "Common Feature Association" technique to produce tabulations of "GROUPs" of contiguous picture elements (STRNGs) in orthogonal orientations. The first GROUPs have STRNGs which lie along the horizontal picture lines. The second set of GROUPs have their STRNGs rotated and so denote the picture elements with like column numbers, and similar gray scale values, and which are contiguous to each other line to line. By comparing the length of the horizontal STRNG to the vertical STRNG in which a picture element within a GROUP resides, the orthogonal direction that presents the smaller problem for interpolation across the GROUP can be determined.

Input and Output. This technique requires the output from the "Common Feature Association" technique. That is, it requires a two gray level silhouette of each GROUP to be interpolated. It also requires the use of the "Frame Rotation" technique (see paragraph 2.3.1.3).

A table is produced for each GROUP to be interpolated. Each table contains one entry for each picture element in the GROUP, and each entry contains the location of the element in the GROUP, the beginning and end points of the STRNG, and the direction in which interpolation should be performed.

Flow Diagram. Figure 2-11 presents a general flow diagram of this restoration technique. The following is a definition of the terms used in that diagram.

I,J	- The line and column number of the picture element in process
STRNGH,STRNGV	- A group of picture elements which have similar gray scale values, and are contiguous to each other along a horizontal line (STRNGH) or along a verticle column (STRNGV).
imax,imin	- The largest and smallest value of (i) in a GROUP
jmax,jmin	- The largest and smallest value of (j) in a GROUP
ITPL	- A table containing the verticle and horizontal STRNGs and the beginning and end points of the interpolation to be performed within those STRNGs
K	- A number which identifies each interpolation path. It indicates the order in which interpolation should be performed
N	- An integer variable used for internal bookkeeping
A,B	- The beginning and end points within each STRNG across which interpolation should be performed
(-j),(+j)	- The first and last element in a STRNG (designated by column number).

Capabilities and Limitations. Because of its complexity, the use of this technique should be limited to the determination of the optimum interpolation path across irregular, non-linear picture features. An examination of each GROUP produced by the "Common Feature Association" technique may by itself indicate the direction in which interpolation should be performed. This is particularly true where the film may have been scratched during processing,

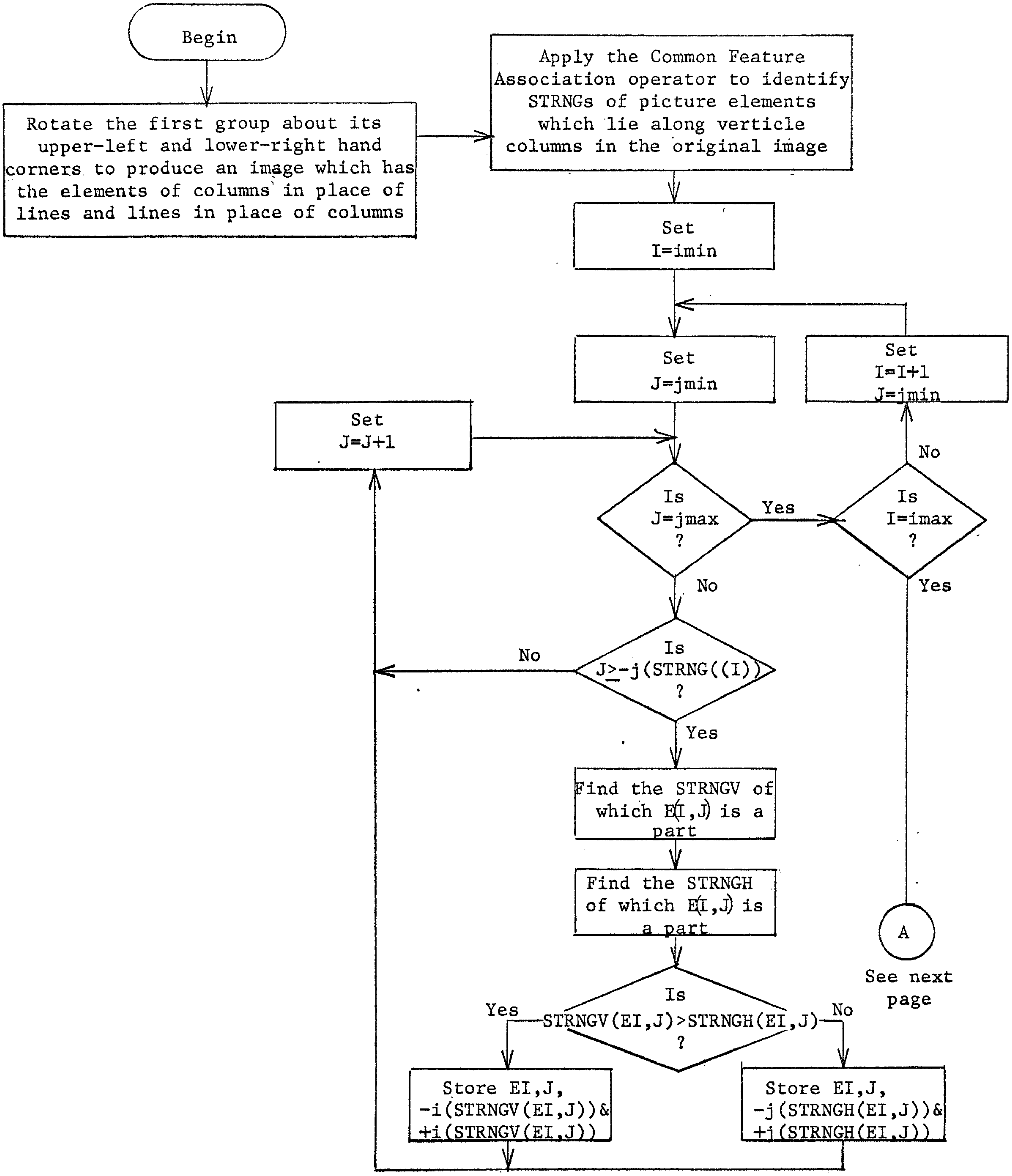


Figure 2-11. Interpolation Path Reduction

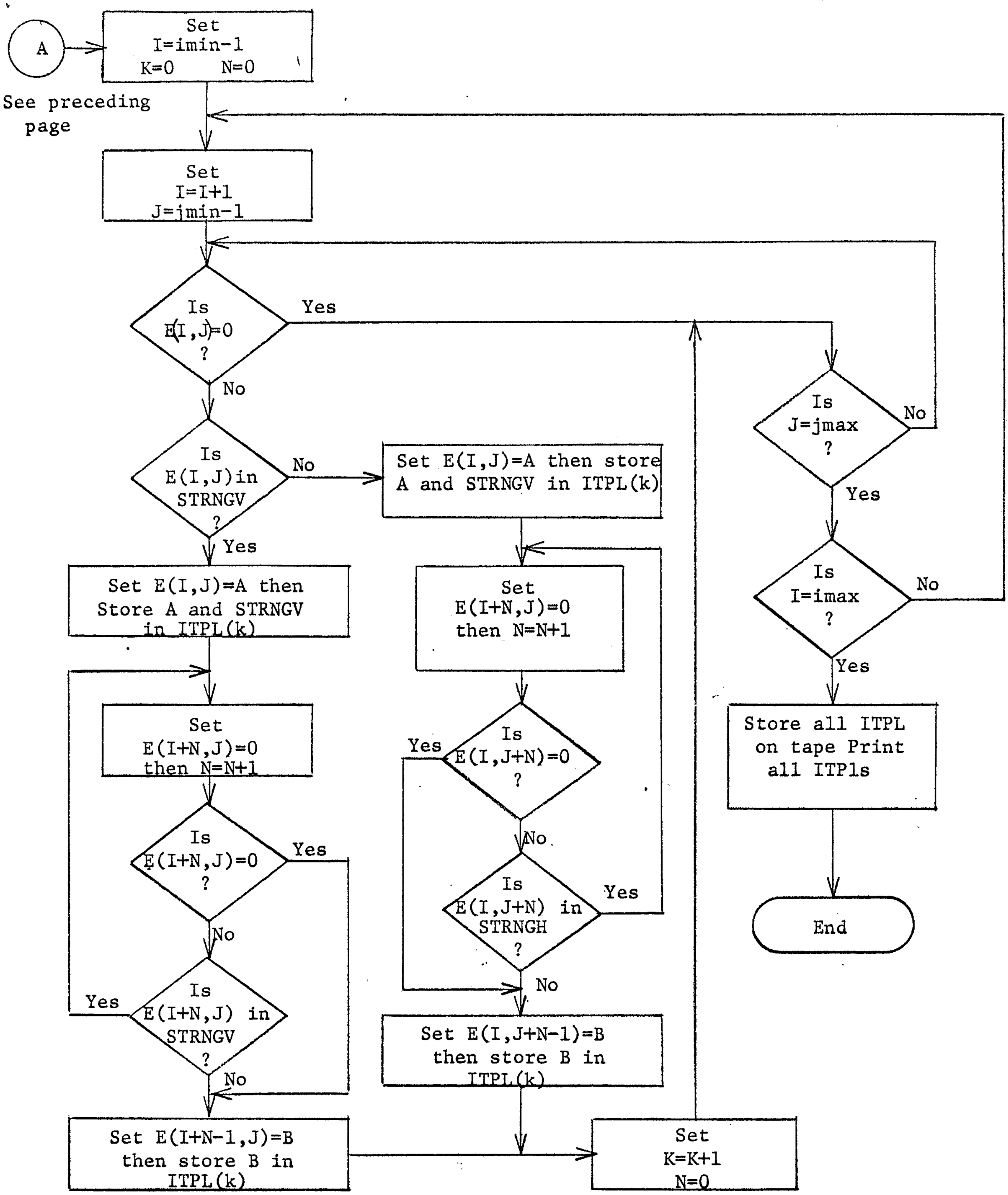


Figure 2-11 (cont). Interpolation Path Reduction or by the transport mechanism during frame change. Such blemishes will usually take the form of parallel lines running approximately at right angles to an edge of the frame.

Existing Off-the-Shelf Software. This technique is specifically designed to be used as a preparatory step for deconvolution. No off-the-shelf software is known to be available at this time.

Estimated Run Time. It is estimated that approximately one-half minute of 7094 time will be required to process a moderately noisy image with this technique. This does not include the time needed for frame rotation or common feature association.

2.2.2.2 Data Interpolation

Purpose. The purpose of this technique is to replace image data that has been lost by interpolating the valid surrounding data thorugh the missing data area, and creating an approximation of the missing data. The technique is particularly useful where the required interpolation path is but a few picture elements wide--such as in the case of a small scratch in the film emulsion.

Operations Involved. It is first necessary to determine the number of data points required for the restoration of a missing data area. This may be accomplished by use of the "Interpolation Path Reduction" technique or, if the missing data has a fairly linear form, by manual methods. The following operations are then performed:

- A measured amount of picture data (along the path of interpolation) is used to withdraw valid data from both ends of the missing data path.
- A string of valid data bits equal in number to the missing data string is incorporated from the original picture into the interpolation process.
- An estimate of the values of specific missing data points is made, based on the valid data from both sides of the missing data area.

Input and Output. Access to the original, unaltered picture in both the upright form and in a 90° rotation form is required. (This allows efficient data manipulation in either vertical or horizontal directions.) Output data generated from the "Interpolation Path Reduction" technique, or manually generated data, in the format of the output of the "Interpolation Path Reduction" technique is also required to describe the interpolation processes to be performed.

An image is generated which has had the missing data area replaced by data which is an interpolation of the surrounding valid data.

Flow Diagram. Figure 2-12 presents a general flow diagram of this restoration technique. The following is a definition of the terms used in that diagram.

K	- A number assigned to each data string for which interpolation is to be performed
length	- The distance along the interpolation path between the boundaries of the missing data area
BGNH,BGNV	- The horizontal and vertical valid data beginning points along the interpolation path. Valid data is taken from these points to the edge of the missing data area
ENDH,ENDV	- The horizontal and vertical valid data end points along the interpolation path. Valid data is taken from the edge of the missing data area to these points.
A,B	- See paragraph 2.2.2.1
(+j)(-j),STRNGH,STRNGV	- See paragraph 2.3.2.3
ITPL	- See paragraph 2.2.2.1.

Capabilities and Limitations. Any interpolation process must be used with caution. The larger the area requiring interpolation is, the more likely that the interpolation data will be different from the original values. Also, if the data which surrounds a missing data area is randomly varying, accurate interpolation of the missing data becomes more difficult. Therefore, care should be exercised in the use of this data. If a space of more than a few data points has been affected in an area of the picture where gray scale values vary widely, it may be wiser simply to mask out the missing data and consider it irretrievably lost than to try to interpolate across the space and introduce gross errors.

Related Off-the-Shelf Software. Data interpolation routines are commonly available as off-the-shelf software packages. Some have been developed for the reduction of data by elimination of every n^{th} data point in a data stream. On image processing, they may be used to enlarge portions of a picture and to fill in missing picture elements. The problem addressed by this technique is primarily that of locating bad or missing data points. Once this is accomplished, interpolation across those points is a minor problem.

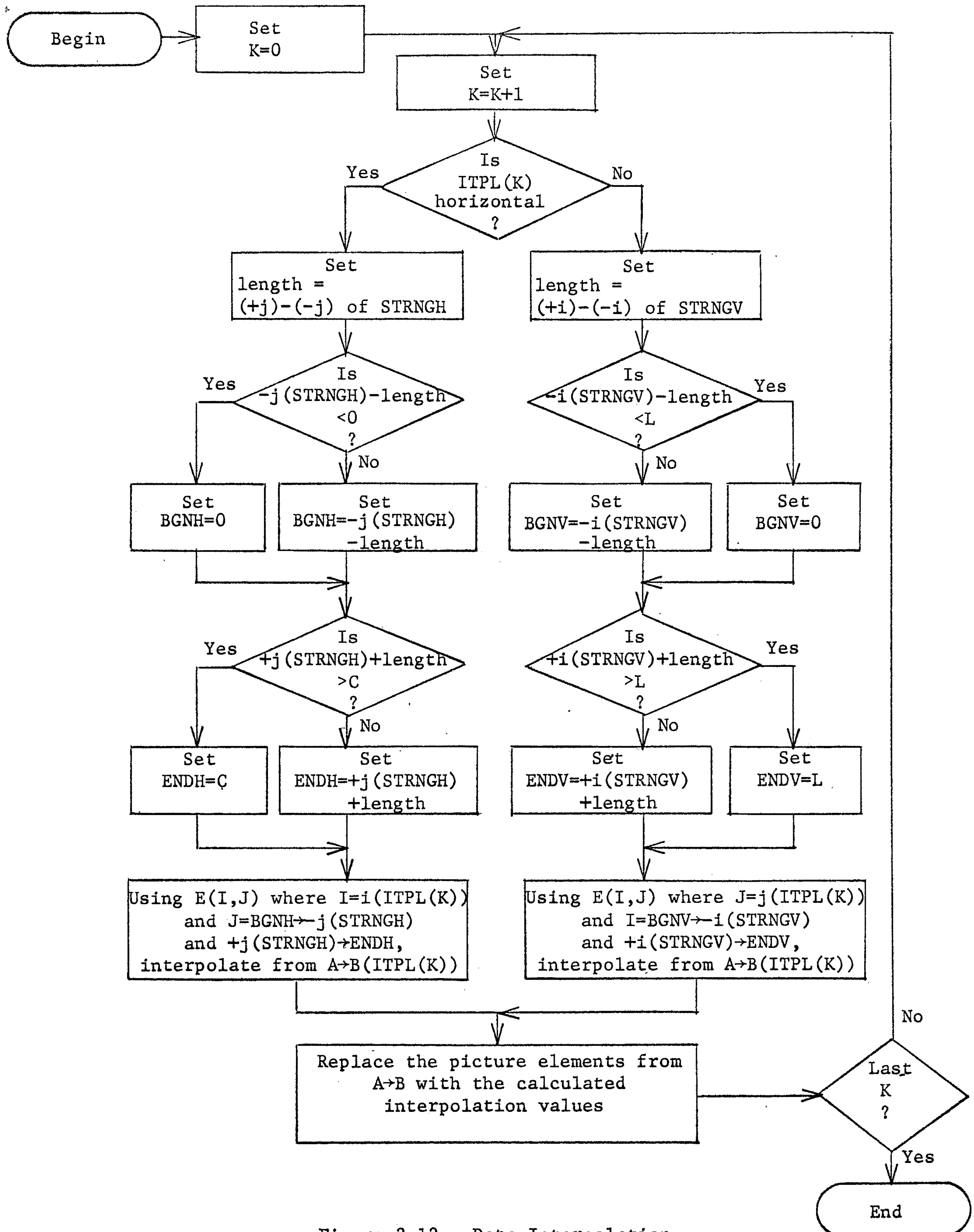


Figure 2-12. Data Interpolation

Estimated Run Time. The estimated time required for a 7094 computer to process even a badly degraded frame by this interpolation technique is small and should not require more than two minutes including I/O.

2.3 Manipulation

A number of image processing techniques have been explored as potentially valuable tools for the analysis and general handling of solar X-ray photographic data. These manipulation techniques are discussed under two classes--those techniques which are used for manipulation of the geometric arrangement of image data, and those photometric techniques which may be useful in the analysis of the solar X-ray photographs.

2.3.1 Geometric Manipulation. Four techniques which are used to manipulate the geometric arrangement of the picture elements within a picture frame are discussed--"Geometric Distortion Correction," "Aspect Ratio Correction," "Frame Rotation," and "Boundary Tracing."

2.3.1.1 Geometric Distortion Correction

Purpose. This technique is useful wherever an imaging process has failed to record object lengths uniformly over the entire field of view such as in the following cases:

- Curvilinear barrel distortion
- Curvilinear pincushion distortion
- Distortion of perspective

Operations Involved. This technique compresses or expands prespecified portions of the picture to correct for various forms of geometric distortion in the following manner:

- The corrections to be performed are described by groups of rectangles. Each group contains three rectangles which are described by the line and column numbers of their corners. The first rectangle of each group identifies the area of the picture affected. The second and third rectangles represent before and after figures within the specified area. By adjusting the relative slope and length of the sides of the latter two rectangles, a wide variety of desired geometric manipulations may be described.

- The picture first is segmented into a number of small areas as prescribed by the first rectangle in each rectangle group. The vertical and horizontal dimension of each area is then adjusted by an interpolation process to correspond with the before and after representation of the second and third rectangles.
- A new picture is created in which line and column segments have been stretched or shortened in compliance with the input rectangles.

Input and Output. In addition to the digitized subject image, correction rectangles must be provided to describe the desired corrections. These rectangles are supplied in sets of three and as many as one hundred sets may be specified. Each set consists of a rectangle which defines the area of the original picture for which the set applies, a rectangle which represents a four sided figure in the original image, and a rectangle which represents that same four sided shape when corrected as a result of the operation on the input rectangle. Each of these rectangles is defined by identifying the line and column number of each of its four corners, beginning with the upper left hand corner and proceeding in a clockwise direction. The output is an image which has undergone the geometric adjustment described by the input rectangles.

Flow Diagram. Figure 2-13 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

Input Rectangle	- Four sets of picture coordinates (line, column) describing a four sided figure in the input image
Output Rectangle	- Four sets of picture coordinates (line, column) describing a four sided figure which has undergone a desired geometric correction
Range Rectangle	- Four sets of picture coordinates (line, column) which describes a four sided area on the input picture to which a specific geometric correction (described by an input and output rectangle) applies
Geometric Operator	- A mathematical expression relating spatial compression or expansion to position.

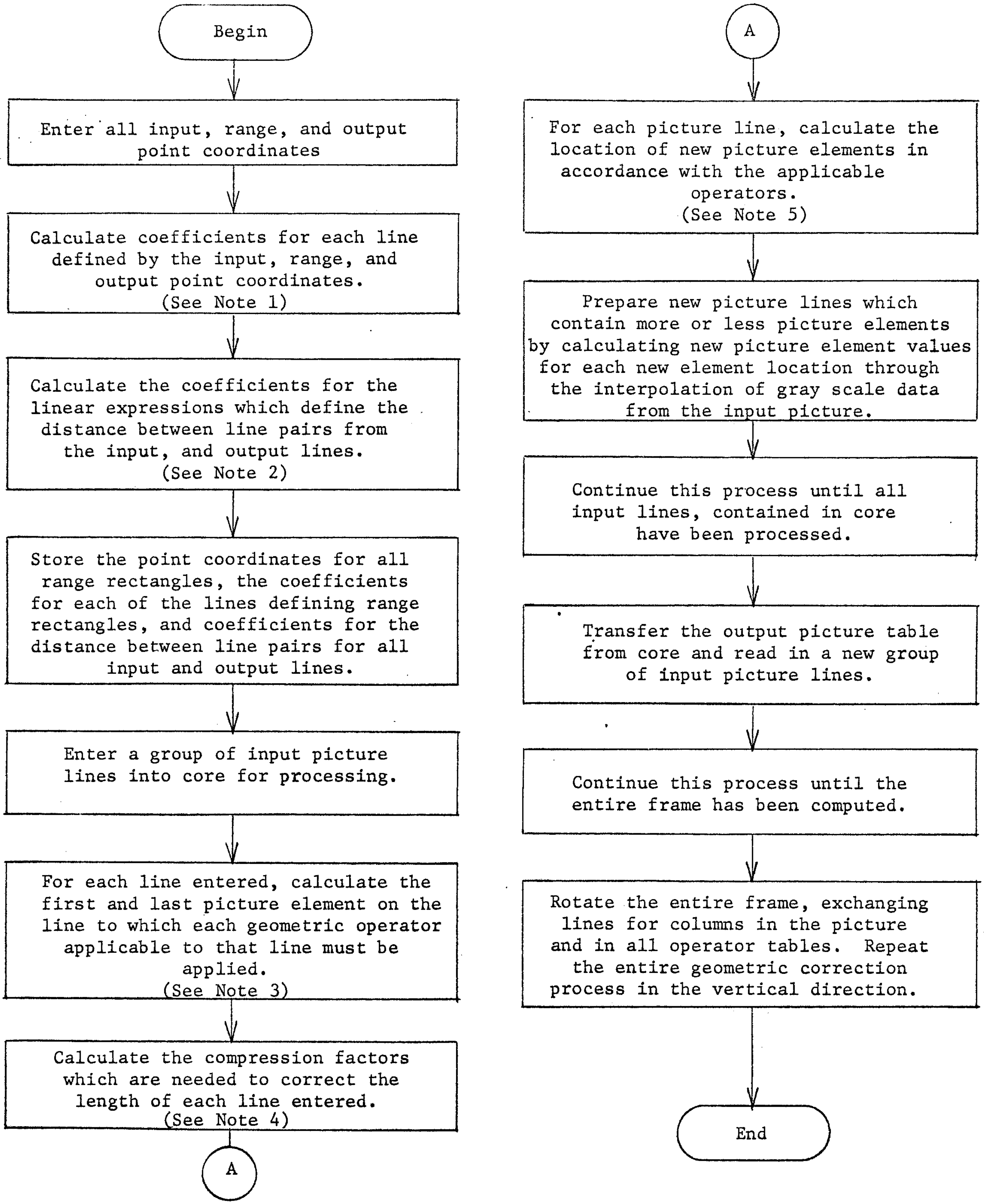


Figure 2-13. Geometric Distortion Correction

Note 1: The four points of the rectangles which are used by this routine to describe desired geometric adjustments actually define four lines which are of interest. Since the coefficients for the linear expression A+BX may be calculated at the beginning of this routine, the following process is carried out for each input, output, and range rectangle:

The four points, m, n, o, and p, which define the rectangles are grouped together and the groups arranged with respect to each other by order of increasing line number for the point m, and increasing column number where two "m" points fall in the same line. The point m is always the point nearest the upper left hand of the frame with the other three points falling in their clockwise order.

For each rectangle, the coefficients for four line equations are calculated as:

$$\text{line m-n} + Mi + \left(\frac{Ni-Mi}{Nj-Mj}\right) J \qquad \text{line P-O} = Pi + \left(\frac{Oi-Pi}{Oj-Pj}\right) J$$

$$\text{line n-o} = Nj + \left(\frac{Oj-Nj}{Oi-Ni}\right) I \qquad \text{line M-P} = Mj + \left(\frac{Pj-Mj}{Pi-Mi}\right) I$$

These coefficients are stored for later use by the routine.

Note 2: The distance between line pairs is the difference between the expression for the lines defining the two opposite sides of the rectangle. For example:

the distance between line N-O and M-P

$$NO\text{-}MP = \left[Nj + \left(\frac{Oj-Nj}{Oi-Ni}\right) I\right] - \left[Nj + \left(\frac{Pj-Mj}{Pi-Mi}\right) I\right]$$

which defines two new coefficients as a function of I

$$NO\text{-}MP = NJ\text{-}MJ \quad \left(\left(\frac{Oj-Nj}{Oi-Ni}\right) - \left(\frac{Pj-Mj}{Pi-Mi}\right)\right) \quad I$$

Note 3: Since all rectangles have been arranged and stored in the order of their upper left hand corner, it is relatively simple to withdraw the line equations for the range rectangles through which any one line passes. Once this is done the intersection of the picture line with the left and right hand sides of the rectangles are computed and stored. This results in a begin and end point for the application of the geometric correction prescribed for picture elements within each range.

Note 4: After the segment of a picture line that falls within a particular range rectangle is identified, a compression factor must be computed for that line segment. This is accomplished by determining the ratio of the length of the picture line between the left and right hand borders of the input rectangle to the length between the left and right hand borders of the picture lines' output rectangle.

For example, if the input rectangle is denoted by m, n, o, and p and the output rectangle by m', n', o', and p' --

$$\text{The horizontal expansion coefficient} = \frac{Nj - Mj + \left(\left(\frac{Oj-Nj}{Oi-Ni}\right) - \left(\frac{Pj-Mj}{Pi-Mi}\right)\right) I}{N'j - M'j + \left(\left(\frac{O'j-N'j}{O'i-N'i}\right) - \left(\frac{P'j-M'j}{P'i-M'i}\right)\right) I}$$

Note 5: As each picture line is entered, and segmented in accordance with the range rectangles, compression factors are computed, and a new line is constructed which contains more, or less elements than the original. The location of each of these new elements, relative to the original picture line segment is calculated by first determining how many elements will exist in the new segment and then calculating the points along the original line segment to which they correspond.

The number of elements in the new line segment (N) equals the number in the original segment (Q) multiplied by the compression factor (S) and rounded to the nearest whole number.

The location of each new element in a segment is equal to its relative position in the segment (n) divided by the compression factor

$$ln = n/s$$

Capabilities and Limitations. This technique is intended to correct for apparent changes in dimensional relationships within an image frame, and as such, it does not provide for correcting any distortion introduced by the translational movement of portions of the image. Care must be taken in selecting the input and output rectangles to prevent portions of the image from being out of the field of view. Also, care must be taken to include within one of the range rectangles all areas of the image to which some correction is desired. Picture elements which have no range rectangles assigned to them will be simple inserted into the output picture unaltered.

Related Off-the-Shelf Software. This technique is patterned after one presently in use by JPL called "GEOM."[8] Many such geometric techniques have been developed for correction of various forms of geometric distortion in images.

Estimated Run Time. It is estimated that approximately twenty minutes of 7094 time will be required to process a single 512x512 element picture utilizing this technique.

2.3.1.2 Aspect Ratio Correction

Purpose. Because the solar surface is imaged on the picture frame as an orthographic projection of a hemisphere on a plane, all dimensions of the image, except those at the exact center of the picture frame, suffer geometric distortion of selected portions of the hemisphere so that true shapes and area calculations may be made.

Operations Involved. The following operations are performed:

- A mosaic of groups of picture elements in generated.
- The distance between the center of each of the groups and the center of the sun is calculated, and the extent to which a radially oriented line segment would appear to foreshorten, when viewed from a great distance, is determined.
- Factors for the correction of the aspect distortion in both vertical and horizontal directions are derived.
- The correction factors are applied to the selected portion of the solar image to produce a picture which is geometrically correct.

Input and Output. In addition to the digitized subject image, the following data must be provided:

- The radius of the sun in terms of the number of picture elements from its center to its limb along a radial from the center.
- A scaling factor which determines the overall size of the resultant image. This should be chosen to keep the processed image within the dimensions which can be handled by other image processes.
- The location of the frame segment which makes up the digitized input image. This is described by locating the upper left corner of the picture with respect to the sun's center, and by specifying the number of lines and columns in the picture.

The output is a digitized image representing the geometrically correct presentation of dimensions and shapes on the solar surface. Center verified, it can be displayed to provide a geometrically correct map of a portion of the solar hemisphere.

Flow Diagram. Figure 2-14 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

- H - The vertical distance from a point in the subject picture to the center of the sun--measured in picture element widths.
- L - |line number of sun's center—line number of the point|
- W - The horizontal distance from a point in the subject picture to the center of the sun--measured in picture element heights.
- C - |column numbers of sun's center—column number of the point|
- STR - The stretch restriction factor which prevents attempted calculations of dimensions near the solar limb.
- g - A scaling factor which dimensions the overall size of the output picture.
- R - The apparent radius of the solar disk--measured in picture elements.
- S - A stretch factor calculated so that the correct image dimension = the foreshortened dimension x (1+S).

Capabilities and Limitations. This technique is valuable in producing a true representation of features on the solar surface. Because conversion of the entire surface of a hemisphere to a plane is impossible, the use of this operator should be restricted to small areas on the sun where the approximations of this algorithm are within acceptable limits.

Related Off-the-Shelf Software. Although a number of techniques for the correction of aspect ratio distortion in aerial photographs of the earth have been developed, an off-the-shelf software package utilizing this technique for solar image aspect ratio distortion has not yet been located.

Estimated Run Time. It is estimated that this technique will require approximately ten minutes of 7094 time to process a single 512x512 element picture.

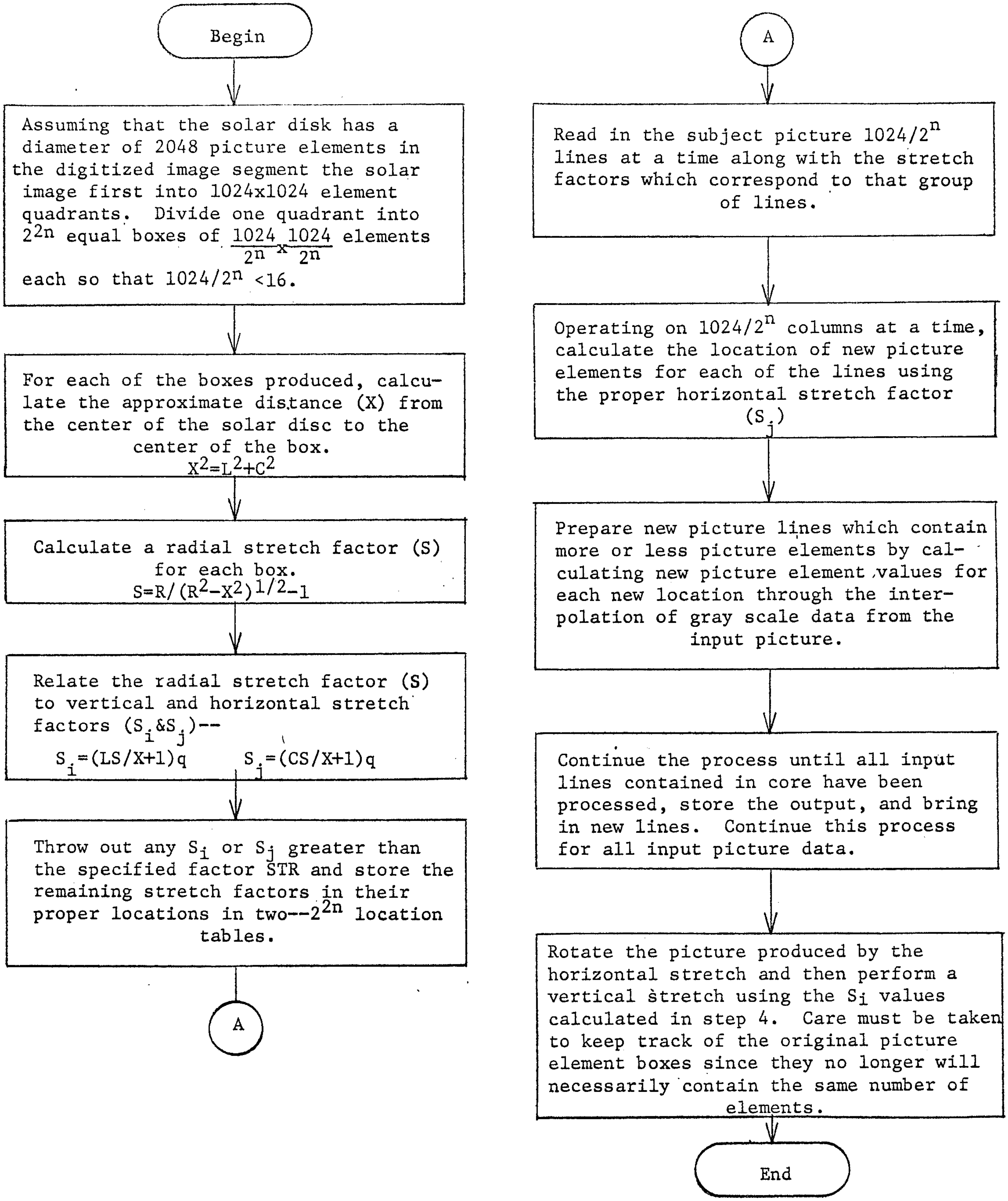


Figure 2-14. Aspect Ratio Connection

2.3.1.3 Frame Rotation

Purpose. Many image processing operations require the capability to move from picture element to picture element along the vertical path as well as the horizontal. Since most pictures will originally be scanned and stored as a series of picture lines, and the size of most image frames prohibits their storage in core in toto, such manipulations become very cumbersome. It is desirable to produce a new picture frame which is an exact reproduction of the original with the exception that the picture elements are arranged in order of increasing column numbers with each line of elements being presented before the next column is introduced. This will allow for the vertical translation from data point to data point by simply calling a second block of data containing all of the lines within a specific picture column.

Operations Involved. This technique utilizes "scratch" tapes or disks to reduce the data transfers needed to strip off each column, line at the time. Once the picture has been broken down into a number of column groups and stored on tape or disk, they are read back into core, column group at a time. Each column group is then read out onto an output tape by column and then line. The geometric effect is that of flipping the image about a line drawn from its upper left hand corner to its lower right hand corner (assuming that the picture is originally scanned from left to right and from top to bottom).

Input and Output. In addition to the original digitized picture image, the number of lines and columns of the original picture, the number of tapes or the amount of disk available, and the amount of core set aside from data storage must be specified.

This technique provides a picture in which the original picture elements $E(i,j)$ have been modified in accordance with the expression:

$$E(i,j) = E(j,i).$$

Flow Diagram. Figure 2-15 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram

- I,J - The line and column numbers of the picture data.
- SPACE - The amount of core space available for the in-process storage of picture data. If packing is used to store several picture elements in a single picture work, this available space may be increased considerably.
- L,C - The number of lines and columns of picture data in the original image.
- K,M,N - Integer variables used to keep track of "scratch tapes or disk," picture lines and columns.
- S - The number of "scratch" tapes or disk storage available for interim storage of image data during processing

Capabilities and Limitations. This technique requires a number of data storage transfers to and from core. Because of this, the processing time for large matrixes may be considerable. The ability to use disk for these transfers reduces the processing time considerably. Unless a large amount of core is available, or unless the machine upon which it is implemented is capable of byte manipulation, it is advisable to pack several bytes per word into core--unpacking for processing as needed.

Related Off-the-Shelf Software. Techniques for frame rotation in this manner are commonly used for image processes requiring both vertical and horizontal data access. Most existing software is written to take advantage of high speed random-access memory disks or drums and, therefore, such existing software may be machine limited.

Estimated Run Time. This technique will require approximately seven minutes of 7094 time to rotate one 512x512 element picture (assuming that no disk or drum is available).

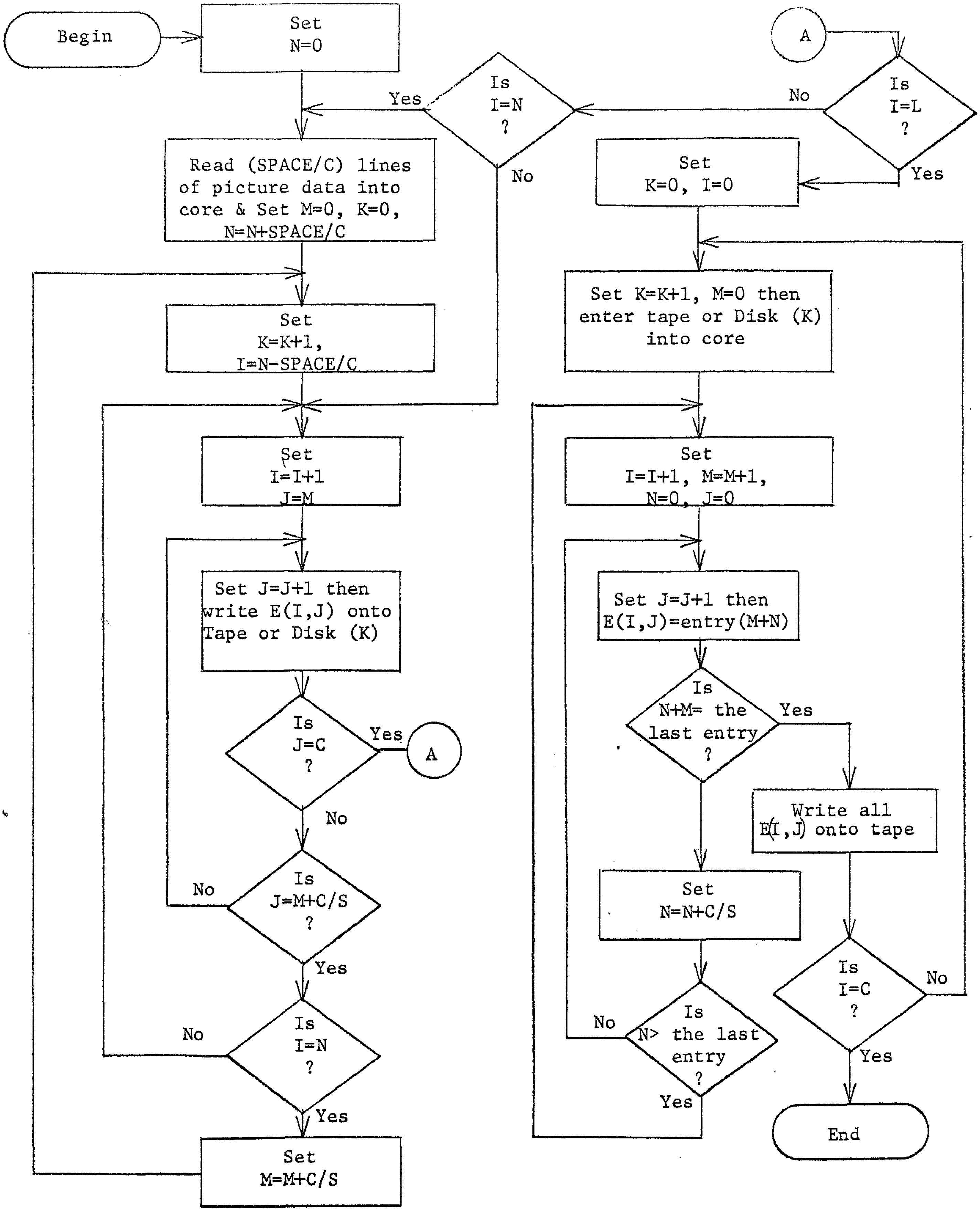


Figure 2-15. Frame Rotation

2.3.1.4 Boundary Tracing

Purpose. The purpose of this technique is to locate and identify data points which have a common gray scale value and which are contiguous to each other. By performing such operations on an image which has been differentiated to produce a density gradient image, boundaries of sharply defined objects on the image may be identified and traced.

Operations Involved. This technique requires that a picture first be differentiated and then threshold limited to produce an image of the borders of sharply defined objects. The following operations are then performed:

- The picture is scanned from top to bottom, left to right until an element with gray scale of 63 is encountered.
- The location of the element is tagged with a GROUP number and stored in a table and the gray scale value of the element is set to zero.
- Each of the eight neighbors of the subject picture elements is next scanned to find a neighbor which also has a 63 gray scale value. This scanning starts at the relative location of the previously identified contiguous element (except for the first of each group where arbitrary starting point is assumed), and continues in a clockwise pattern around the central element.
- This procedure continues with the identification, location, and tabulation of contiguous picture elements until no contiguous neighbor can be found for an element. When this occurs the routine returns to the starting location for that group and continues the scan of the picture as in the first step.

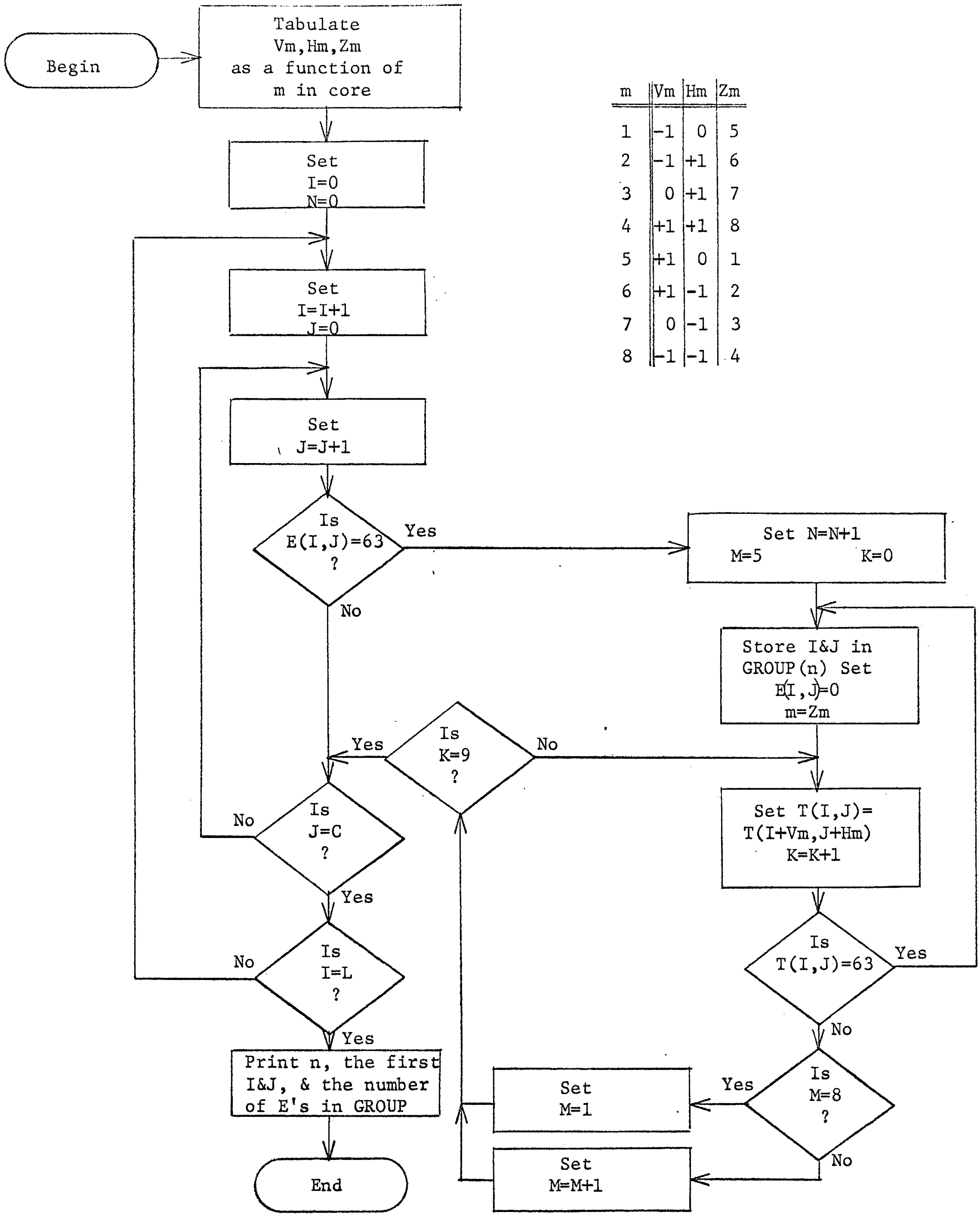
Setting the gray scale value of each tabulated picture element to zero after it has been located and assigned to a GROUP insures that no element will be included in more than one group.

Input and Output. This technique requires an image which has been differentiated and threshold limited to set all values of the picture to zero gray scale except for those which constitute the boundaries of the object to be traced. The boundaries of such objects are set to 63 (gray scale) by the same threshold technique. A record of all picture elements which are the contiguous border elements of an object is produced. Such contiguous picture elements are grouped together and given a GROUP number and the upper left most element of each group is printed to give a rough indication of the location of the group within the frame. The number of picture elements in each group and the number of groups in the frame are also printed.

Flow Diagram. Figure 2-16 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

I,J	- The line and column number of the picture element in process
L,C	- The number of lines and columns in the frame
Wm,Hm,Zm,M&K	- Factors which are used to systematically scan the eight neighbors of a picture element in a clockwise manner, beginning with the previously identified contiguous picture element in the group.
n	- The number assigned to identify each group of contiguous picture elements.

Capabilities and Limitations. This technique is strictly limited by the input data to which it is applied. If an object can be differentiated, and threshold limited in such a manner as to produce a well defined, narrow boundary around the object, the operator should produce very good results. If, however, the boundaries of the object are poorly defined (this is to be expected in the X-ray telescope experiment), a considerable amount of manual manipulation of input data may be required before satisfactory boundaries can be established for each object.



m	Vm	Hm	Zm
1	-1	0	5
2	-1	+1	6
3	0	+1	7
4	+1	+1	8
5	+1	0	1
6	+1	-1	2
7	0	-1	3
8	-1	-1	4

Figure 2-16. Boundary Tracing

Related Off-the-Shelf Software. This technique is similar to one used by R. S. Ledley to define chromosomes[9] and a working software package based on his technique is on hand at MSFC.

Estimated Run Time. This technique is severely limited for use on a machine possessing no high speed random access storage. It is estimated that approximately ten seconds of 7094 time would be required to process a 512x512 element picture if no tape or disks transfers are included in the estimate. The total time, therefore, is almost purely a function of I/O.

2.3.2 Photometry. Several techniques have been studied which appear to have potential value as tools for the analysis of solar X-ray photographs--Area Calculation, Centroid Calculation, and Common Feature Association.

2.3.2.1 Area Calculation

Purpose. The purpose of this technique is to calculate the total area within a picture frame where the gray scale value is within certain prespecified levels. Since picture density can be related to X-ray intensity for this experiment, the total area of X-ray emission within certain levels is valuable in calculating the X-ray flux density of solar emissions.

Operations Involved. This technique utilizes the Common Feature Association technique to tabulate the boundaries of contiguous picture elements within a frame. Each GROUP of picture elements is then processed by counting the total number of picture elements in the STRNGs that make up the GROUP (see paragraph 2.3.2.3).

Input and Output. Only the output from the Common Feature Association technique is required as input data. That is--a tabulated listing of each GROUP of non-zero picture elements which are contiguous to each other must be provided. The Area Calculation technique outputs list of the picture element GROUPs along with the corresponding area of each of those groups.

Flow Diagram. Figure 2-17 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

AREA - The area calculated for each picture GROUP

GROUP - A group of picture elements with gray values within specific limits which are contiguous to each other

STRNG - A series of picture elements within a GROUP which have the same line number and are contiguous to each other

N - The number of the GROUP being processed.

(-j),(+j) - The column number in which each STRNG begins and ends. (See paragraph 2.3.2.3)

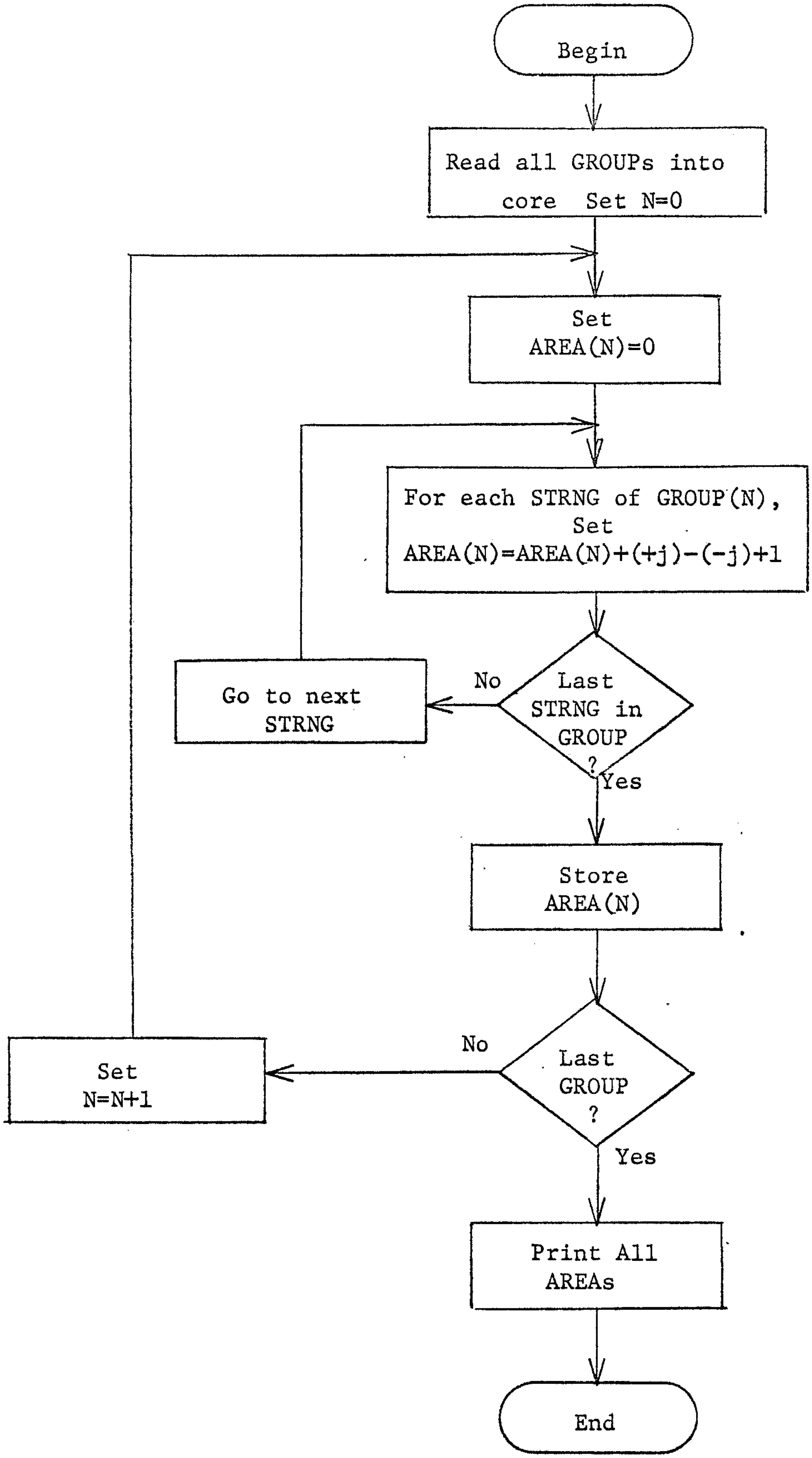


Figure 2-17. Area Calculation

Capabilities and Limitations. The effectiveness of this technique is primarily dependent on the input data. Therefore, if the data produced by the "Common Feature Association" technique is valid, the results obtained from performing these operations should be equally valid.

Related Off-the-Shelf Software. This technique is similar to a portion of one used by Agarwal[10] for the automatic detection of solar flares and is, therefore, available as a part of a larger program at MSFC.

Estimated Run Time. It is estimated that this technique will require less than one minute of 7094 time to process one 512x512 element picture. This does not include the time required for the "Common Feature Association" operations.

2.3.2.2 Centroid Calculation

Purpose. In order to determine the translational rate of movement as opposed to a rate of growth or decay of a solar feature, some point of reference is needed. This technique calculates the location of the centroid of each feature and identifies its location by line and column numbers.

Operations Involved. In order to make the centroid calculations more efficient, the output from the "Common Feature Association" technique (see paragraph 2.3.2.3) are sorted by GROUP in order of increasing line number with the elements of each line appearing in the order of increasing column number. The GROUPs are also sorted in order of increasing column numbers and line numbers. The following steps are then performed:

- The number of elements in each STRNG are counted and multiplied by the vertical distance to the top of the frame (the line number) and summed together.
- The number of elements in each string are also multiplied by the distance between their center element and the left hand edge of the frame, and summed together.
- After the totals for all STRNG's of all GROUPs have been calculated, the results are divided through by the AREA of each group to produce the I and J coordinates for the centroid of each GROUP. The AREA must be calculated utilizing the Area Calculation technique (see paragraph 2.3.2.1).

Input and Output. This technique requires that the Common Feature Association technique be used to locate and group contiguous picture elements and the Area Calculation technique be used to determine the area of each GROUP. The output from these techniques are required as input to this technique, which produces as output, a list of vertical and horizontal position coordinates of the centroids of each GROUP. These coordinates are measured from the top and left hand edges of the frame in units of picture element length.

Flow Diagram. Figure 2-18 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

GROUP - A group of picture elements within prespecified gray limits which are contiguous to each other on the frame

STRNG - A row of contiguous picture elements in the same line of a GROUP

TOTL - The coordinate position of the GROUP centroid. There are two TOTLs (V&H) for each GROUP

M,N - Integers used by the operator for keeping track of STRNGs and GROUPs

(-j),(+j) - The column number in which each STRNG begins and ends (see paragraph 2.3.2.3).

Capabilities and Limitations. This technique is heavily dependent on the data used in its calculations. Thus the accuracy of the location of the centroid of a GROUP depends on the accuracy of the location of the boundaries of that GROUP.

Related Off-the-Shelf Software. This technique is similar to a portion of a technique used by Agarwal to automatically detect solar flares[11] and is on hand at MSFC.

Estimated Run Time. It is estimated that this technique will require less than one minute of 7094 time to process a single 512x512 element picture. This estimate does not include the time required for the "Area Calculation" or "Common Feature Association" techniques which are used.

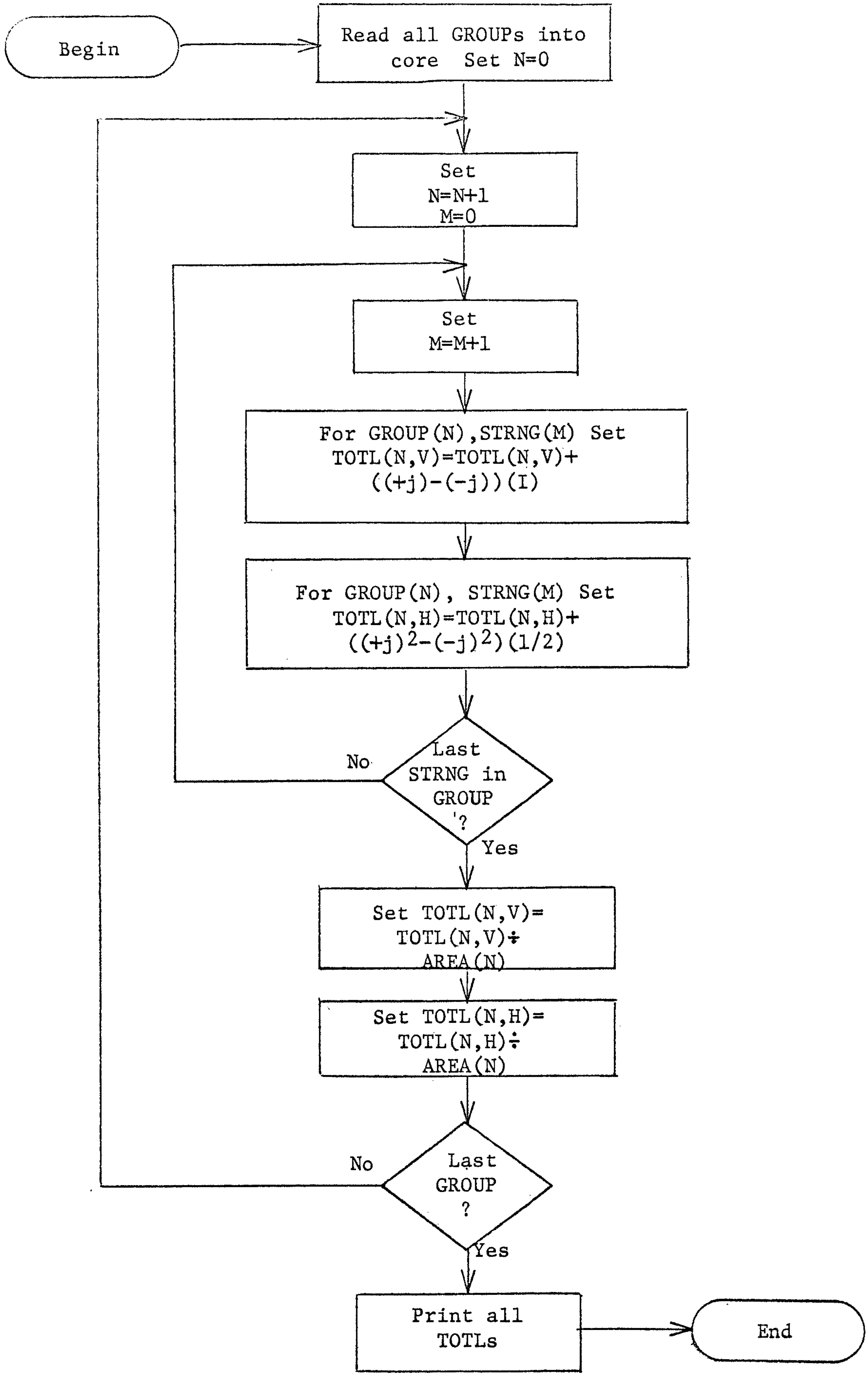


Figure 2-18. Centroid Calculation

2.3.2.3 Common Feature Association

Purpose. The purpose of this technique is to identify a group of picture points which are related to each other by virtue of their gray scale level and their proximity to each other and to determine the boundaries of the figures which these points define. Such a technique is necessary if reasonably accurate measurements of velocity and rate of growth of solar features are to be calculated.

Operations Involved. This technique relies on the "Gray Scale Limiting" technique (see paragraph 2.1.3.3) scanning the frame and setting all picture points below a prespecified gray level to zero gray value. The following steps are then performed:

- The picture is first scanned a line at a time, and all picture elements which have non-zero gray value and which are contiguous to each other are tabulated.
- The STRNGs of contiguous picture elements are then scanned and those STRNGs which overlap each other, line to line, are tagged as belonging to a common feature or GROUP.
- By making two passes through the table of picture STRNGs, from top to bottom and from bottom to top, all picture points within common solar features can be identified.

Input and Output. The only input data needed is the output of the "Gray Scale Limiting" technique. That is, a picture frame is required in which all picture element gray scale values outside of a specific range of levels have been set to zero gray value. This technique first produces a table of picture element locations. The table identifies a number of "GROUPs" which correspond to individual picture features and then lists the "STRNGs" of picture elements which make up each "GROUP." The operator then plots each "GROUP" as a silhouette of each picture feature.

Flow Diagram. Figure 2-19 presents a general flow diagram of this manipulation technique. The following is a definition of the terms used in that diagram.

I,J	- The line and column number of the picture element in process
STRNG	- A group or string of picture elements within a picture line which are contiguous to each other
M,m	- An integer assigned to each STRNG for identification purposes
GROUP	- A group of STRNGs which overlap each other, line to line, and thus constitute a single picture feature
N,n	- An integer assigned to each GROUP for identification purposes
L,1,&K	- Integer variables used by the operator for keeping track of the last STRNG in a GROUP, the STRNG being tested for overlap, and the GROUP to which 1 belongs
(-J),(+j)	- The column number in which each STRNG begins and ends.

Note: The operations depicted in Figure 2-19 are for a single pass through the frame from top to bottom. In actual use the operations displayed on the second page of the flow diagram would be repeated for a scan from bottom to top and the results would be combined with the first scan by performing a logical "OR" on all identified GROUPs and combining the GROUPs which have common STRNGs.

Capabilities and Limitations. This technique requires a picture composed of a small number of compact forms. If the picture is of such a structure as to yield a large number of distinct features, the GROUP generation algorithm may saturate the available storage. If the picture is made up of overlapping features of similar gray scale value, the operator will classify all features which overlap as one GROUP. Because of these and similar limitations this technique should be considered as only a first step of feature extraction. It may be necessary to manually segment a GROUP into several distinct features after the output from this technique has been studied.

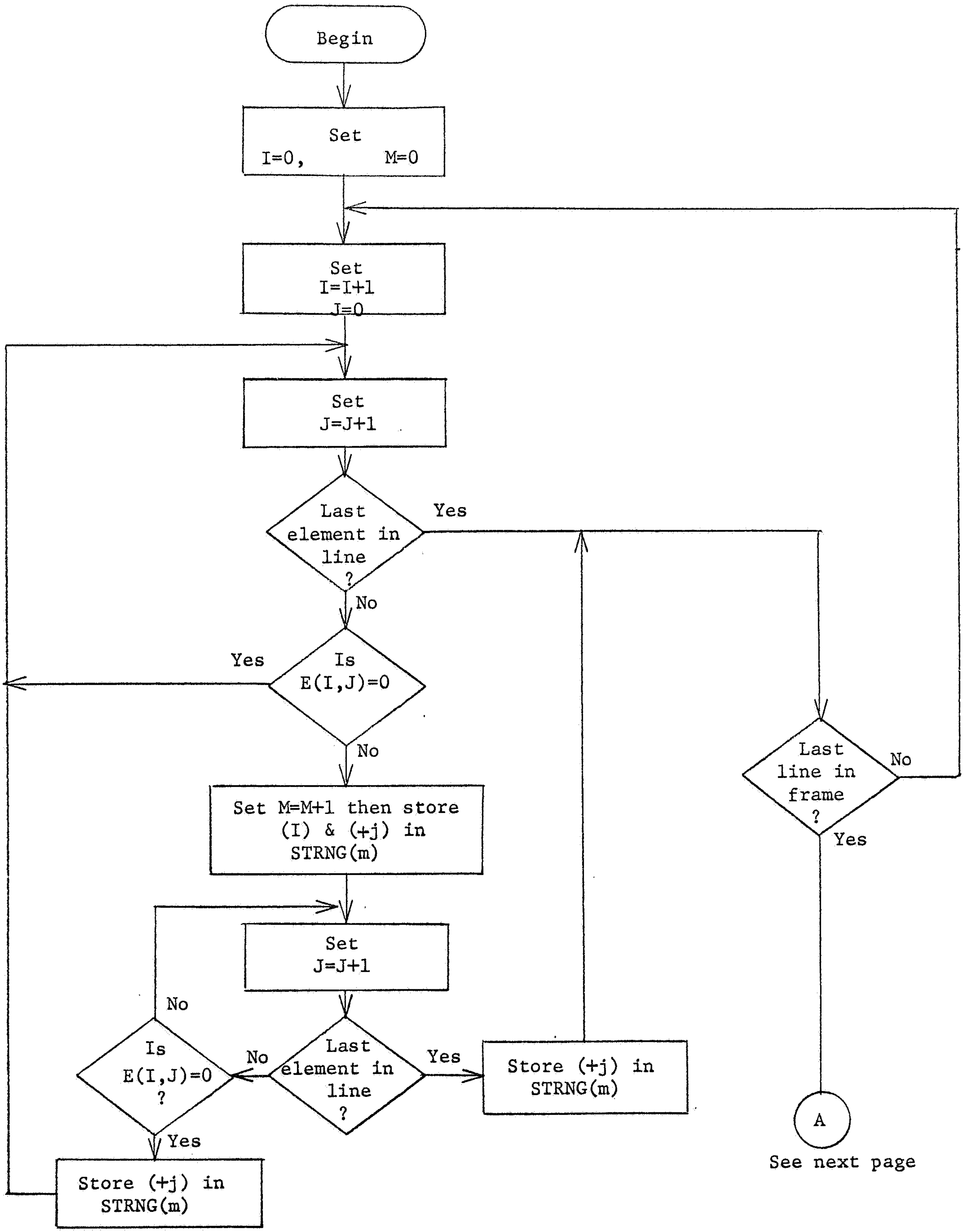
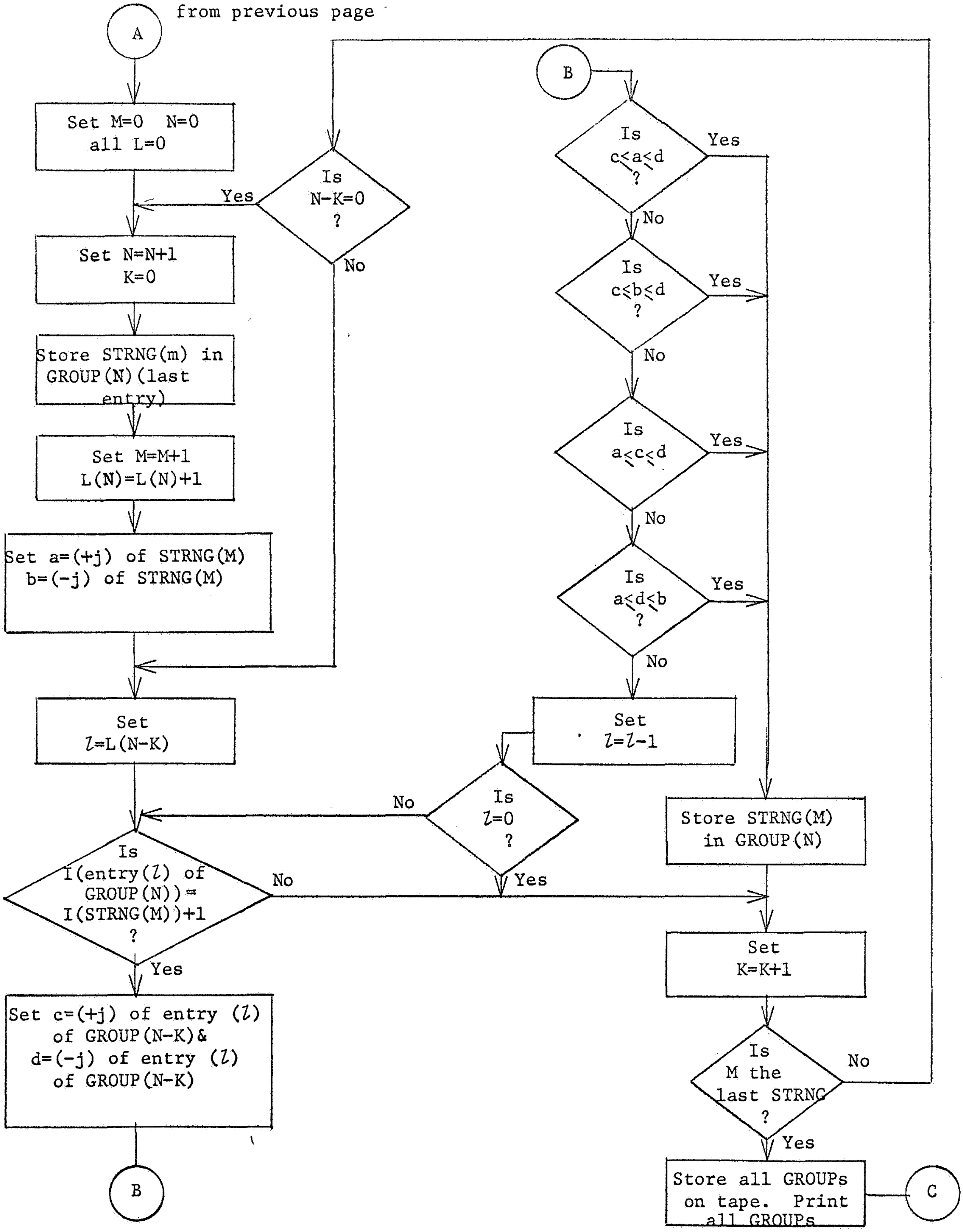


Figure 2-19. Common Feature Association



see next page

Figure 2-19 (cont). Common Feature Association

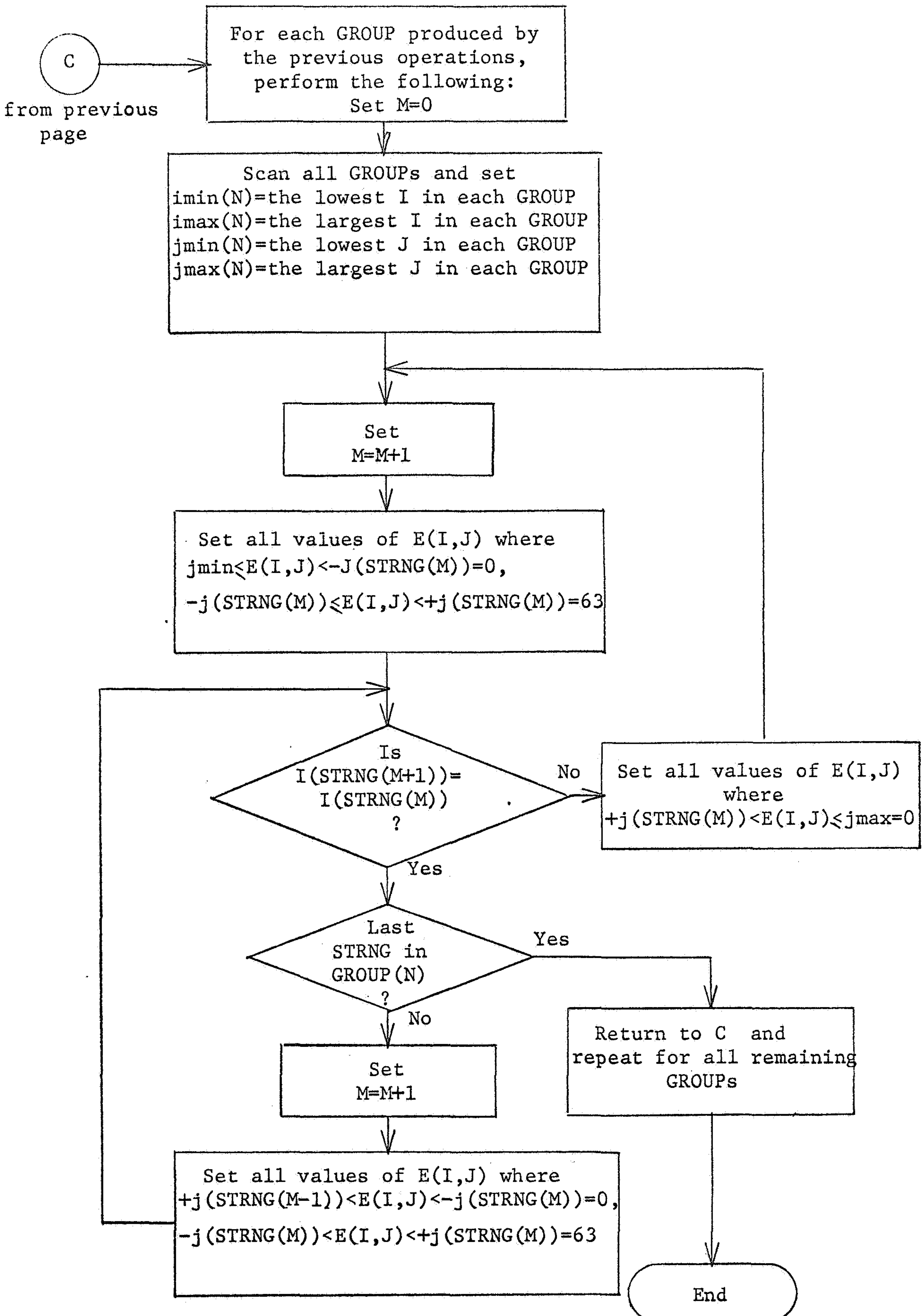


Figure 2-19 (cont). Common Feature Association

Related Off-the-Shelf Software. This technique is similar to one employed by Agarwal for the automatic detection of solar flares.[12] An operational version of this technique is on hand at MSFC.

Estimated Run Time. It is estimated that this technique will require less than one minute of 7094 time to process a single 512x512 element picture.

SECTION 3. HARDWARE

In presenting the software techniques for the processing of image data from an X-ray Imaging Solar Telescope Experiment, care was taken to minimize any discussion of hardware. Realistically, however, data processing hardware and software are closely related, and the peak performance of the system as a whole can only be approached when one compliments the other. This is particularly true in the digital processing of image data. This section presents a discussion of some of the hardware considerations that must be taken into account in developing an image data processing system.

3.1 Component Elements

The image processing system description which follows is tailored to the needs of a single experiment. Implementation of such a system should consider the particular requirements for performance of such a specialized configuration, as opposed to the more cost effective use of a general purpose image processing facility. The system is broken down into the following hardware subsystem:

- Film Scanner
- Central Processing Unit
- Data Storage
- Display and Control
- Special Hardware

3.1.1 Film Scanner. Three basic types of film scanners have been considered for this experiment--a flying spot scanner, an optical mechanical scanner, and a laser scanner.

A flying spot scanner which utilizes a cathode ray tube with computer controlled deflection circuitry and direct computer interface, offers a number of significant advantages. The ability to direct the beam to any desired position of a frame and to read the picture element gray level directly from the scanner can drastically reduce overall processing time. Then too, if the deflection circuitry can be made sufficiently responsive, and if an automated frame change mechanism is provided, the requirement for bulk data storage may be reduced or eliminated. There are a number of factors which may make this approach unrealistic, however. In present day flying spot scanners, as the spot moves from place to place on the tube, its size, shape and intensity varies. Also, nominal spot intensity is low and a good deflection coil for such existing scanners can add as much as one hundred pounds to the weight of the scanner.[13]

Several good optical mechanical scanners are presently available which represent about the optimum in scanner technology where resolution, accuracy, low noise and cost are more important than speed. Most off-the-shelf scanners require a considerable amount of manual manipulation but several automated designs have performed admirably in unmanned reconnaissance satellites, and where high volume data handling is not a problem, scanners employing an optical-mechanical technique offer a good combination of noise rejection, resolution and economy.

Scanners based on laser technology offer significant advantages. Since the laser is an almost ideal light source, it can be focused to a spot size which is diffraction limited and can be controlled to produce such a spot with uniformity of intensity, size, and shape over the entire image frame. Scanning the spot is somewhat more complex than for a flying spot scanner, however, since such scanning is done by mechanical methods such as with rotating mirrors. With the present rate of growth in laser technology, an optical-laser scanner will probably represent the best device for scanning photographs from the Space Station experiment.

3.1.2 Central Processing Unit. The processing of image data places special demands on the general purpose digital computer. The ideal image processing computer should possess a byte manipulation capability. That is, it should allow for logical and mathematical operations on single bytes of data of six or eight bits without having to mask out a portion of a computer word in the process. The image processing machine should have an instruction set which is tailored to the logical and mathematical manipulations common to the processing techniques to be employed. Since the processing of image data requires the handling of vast numbers of data bits, machine speed should be as fast as possible.

The use of parallel element processors should be examined for the possible application to image data processing. By carrying out a number of similar operations on several picture elements at the same time, such parallel processing arrays may be able to significantly improve the processing capability of present processors in handling image data.

By tailoring machine memory to the image data format, data storage and retrieval may be made more efficient, particularly if the core matrix is made compatible with the picture scan matrix. For instance, a memory which is made up of six core planes, each plane corresponding to one of the six bits of the picture element byte, and containing an n x n array of locations which correspond to the n x n array of a picture frame could be addressed with much greater efficiency than a conventional memory stack. Ideally, the computer should possess a working memory which is at least as large as the number of bits contained in one digitized image frame. Since this is in most instances prohibitive, a large memory with an efficient disk or drum core swap capability should suffice.

3.1.3 Data Storage. Two types of data storage are needed for the image processing system. A very high transfer rate disk or drum should be provided so that blocks of image data may be read into or from core as quickly as possible. Access to core should be through a separate memory bus and all such data flow should be controllable independently of CPU attention. Bulk storage of data may be provided by the conventional magnetic disks or tapes or, if improvements in technology allow, by optical storage on film or through holography.

3.1.4 Display and Control. A specialized display/control console should be provided which has the capability to scan films, store the image data in any of the available storage locations, perform digital image processes on the data and to view the resultant pictures as either quick-look CRT displays or in hard copy. Special attention should be given to those devies, such as the light pen, which may be used to carry on the man-machine interaction required by various image processing techniques.

3.1.5 Special Hardware. A number of speical purpose black boxes are presently available and being used to do image data processing. Hardwired devices to assist in convolution processing and two-dimensional Fourier transformation have already proven their value in present data systems. Such devices should be investigated for cost effective use in processing the X-ray photographs on board the Space Station.

3.2 General Comments

This discussion has spotlighted the requirements for hardware needed to process image data from a particular experiment. It is recongized that a facility such as the proposed Space Station must consider the needs of a number of simultaneous investigations and therefore the image processing facility must be made to serve the image processing needs of a number of experiments. There may be cases where the use of the optical properties of coherent light can process an image with far greater efficiency than can be accomplished digitally.[14] In actuality, however, the system which will ultimately evolve for the processing of image data in space will probably make use of optical as well as digital technology.

SECTION 4. OBSERVATIONS AND CONCLUSIONS

The project team has now spent over a year studying the use of digital computer to support experiments in space. Particular attention has been given to those problems associated with the handling of image data. Some comments of a general nature are offered concerning space experiment image data processing.

One cannot say when some breakthrough in technology will significantly change the prospects for image processing in space. A reasonable projection of the present rate of development of image processing related hardware and software would certainly indicate, however, that some fairly sizable portion of image data produced by space experiments scheduled to fly during the next decade may be processed in space. The exact level is unknown. The proportion of experiment image data that it may be profitable to process in space, rather than on the ground, also is unclear. On the one hand, it behooves the experimenter to reduce his data transmission requirements and eliminate possible noise sources by processing in space. On the other hand, there is a reluctance on the part of many experimenters to give up the raw data that is generated by experiment instrumentation. Then too, the size and other physical characteristics of an automated image data processing facility, capable of performing sizable portions of the total experiment image processing is unknown.

In order to prepare for the coming generation of image processing, certain tasks should be undertaken now.

- The investigation and design of software techniques for use in space should begin immediately. Traditionally software has been the last problem solved in a system design, and it is the software development which always seems to take a little longer than expected.

- Many software techniques, such as the ones discussed in this report, can be identified which will have applicability in space. Work should begin now to develop and test image data processing software modules for use in future space programs.
- A facility should be considered for the development and validation of such software.
- Studies should be made of the possible use of various configurations of computer hardware for image processing. Consideration should be given to such arrangements as the parallel element processor concept as possible candidates for improving the speed and efficiency of image processing operations.
- A concerted effort should be made to consolidate experiment requirements into a common Space Station design which would derive benefit from the use of a multipurpose image processing facility on board the Space Station.
- Efforts should be started to find better ways to validate image processing software in a timely and cost effective manner so that there can be no opposition to the use of on-board processing of data on the grounds of reliability, responsiveness, or cost.

REFERENCE LIST

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